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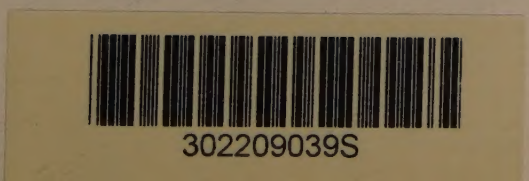

THE PHYSIOGRAPHICAL EVOLUTION OF BRITAIN

BY

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LONDON

EDWARD ARNOLD & CO.

1929

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Made and Printed in Great Britain by
Butler & Tanner Ltd., Frome and London

PREFACE

It is a serious matter to venture into print on a subject of which so many items have been, or still are, open to more than one interpretation. I am only emboldened to make the attempt by the knowledge of the friendly spirit in which my fellow-geologists are wont to treat the controversies of our science.

My aim in writing this book has been to fill a certain gap in student-literature. Many works deal with the processes of change that are *at present* in progress on the earth, and attempt to explain the origin of the physical features of the crust as we see them *to-day*. Only a few—conspicuously *The Building of the British Isles*, by Jukes-Browne—aim at elucidating the *past* geographies of our country, and even these refer in the main only to the distribution of land and sea, the general climatic conditions and the type of life at the different periods. In the present volume these aspects of palæogeography are dealt with in outline, and mainly with the object of obtaining the background of a picture, in the foreground of which I have tried to place the physiographical processes that were at work in those surroundings, moulding and modifying the surface of the earth from period to period in those far-off days. The vividness of the picture depends on the degree to which the individual rocks have been studied, and on the completeness of their record. From them we know more about the constructive than about the destructive processes, more of what went on in the seas than on the land, and more perhaps about the ceaseless gentle movements of the crust than about the paroxysms by which it has occasionally been tortured.

The many vicissitudes through which the British region has passed have made our islands a wonderful storehouse of material for such a study. Would that I felt confident enough that I have done justice to the subject, to dare to dedicate my book to the generations of enthusiastic workers who have hammered out the information that I have drawn upon. I must express my indebtedness to them all, living and dead. The abundant references will guide readers to the original sources in many cases; and, where possible, literature has been cited that contains full references on the subject under discussion. These points should increase the value of the book to geological students, while I hope that the treatment is sufficiently general to appeal to those interested in physical geography and geomorphology.

I want to tender my thanks to the following authors for granting me permission to use illustrations from their works, and to their publishers and various learned societies for allowing me to reproduce them: Mr. E. B. Bailey, Prof. P. G. H. Boswell, Prof. L. Collet, Prof. W. M. Davis, Prof. A. Gilligan, Mr. J. F. N. Green, Prof. W. H. Lang, Mr. W. H. Laurie, Prof. J. E. Marr, Dr. D. Parkinson, Prof. H. H. Swinnerton, and Mr. W. B. Wright. In many instances also I have used published illustrations as a basis for my figures. The source is acknowledged in each case, but my thanks are none the less due to the authors.

I must also record with gratitude the help I have had from Dr. Bernard Smith, Prof. W. S. Boulton, Dr. F. Raw, Mr. Linsdall Richardson and other friends, who have read and criticized different parts of the book at various stages in its construction. Finally, I want to thank my son, who has helped me in various ways, and my wife, severe critic and gentle encourager, who has throughout helped me with head and hand.

L. J. W.

University of Birmingham,
October, 1929.

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PLATE II

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LIST OF ABBREVIATIONS

USED IN THE REFERENCES

G. of Y., *Geology of Yorkshire*, by P. F. Kendall and H. E. Wroot; *P.G.A.*, *Proceedings of the Geologists' Association; P. of S.*, *Principles of Stratigraphy*, by A. W. Grabau; *Q.J.G.S.*, *Quarterly Journal of the Geological Society; Traité*, *Traité de Géologie*, by E. Haug.

THE PHYSIOGRAPHICAL EVOLUTION OF BRITAIN

CHAPTER I

GENERAL INTRODUCTION

There are many angles from which to view Geology; but in the following pages it is the *physiographical* and *stratigraphical* aspects that are stressed.

The word **physiography** literally means the description of nature. It is usually more particularly applied to the study of the surface of the solid globe (lithosphere), the water (hydrosphere), and the air (atmosphere) that make up our earth. It concerns itself with the interaction between these three elements, with the factors that control that interaction, and with the resultant changes. Animal and plant life, and even human activities are ultimately governed by their physical surroundings; and thus must form part of the subject, just as much as do the astronomical relations of the earth in as far as these affect the conditions on its surface.

Physiography is usually limited to a study of *present-day* conditions of the earth; but since the days of Hutton and Lyell it has been recognized that the present processes of change on the earth's surface and within its crust are the same that have functioned throughout the greater part of geological time, and that a knowledge of them provides the key to the understanding of how rocks have been formed and modified in the past. This is the *Uniformitarian Principle*. Its acceptance does not prevent us from acknowledging that the intensity and rate of action of certain processes may at various times have been greater or less than at the present: however much the tempo may have changed, the theme has persisted.

For these reasons the geologist must study and be conversant with present-day physiographical processes. On the other hand, the physiographical conditions of to-day cannot be fully comprehended without taking into account their antecedents which are revealed by a study of the geological record. For this reason the physiographer and geographer must study geology. As Salisbury says:[1] "The

[1] R. D. Salisbury, *Physiography for Schools*, 1909, p. 1.

history of the earth has been written in the rocks for the student of geology, and physiography deals with the latest chapter of that history, the history of the present surface."

Stratigraphy is the branch of geology whose special aim is to elucidate the *history* of the earth. That history may be thought of as an ever-changing series of geographies, each with its current physiographical conditions, including its characteristic life. The geography of each period can be pictured, however dimly, by piecing together innumerable scraps of information supplied by a study of the rocks of that age; but it must be remembered that geographical conditions are not static: they are always changing, and owing to the slowness of the changes they are often barely perceptible within the limits of what we call the present. But the time-factor introduces grave difficulties when we are dealing with protracted geological periods; for while our task is to reconstruct the physiographical conditions that prevailed during a series of consecutive short epochs, we can seldom be certain that the phenomena which we assign to each reconstruction were strictly contemporaneous. Supposing the reconstructions to be true ones, each of these successive geographies becomes an episode in the long history of the world, and can be fully understood only when it is considered in relation to the one before and the one after. Each may indeed be likened to a single picture on a kinematograph-film, which is complete in itself, yet when taken in conjunction with its predecessors and its successors at once acquires a new and living significance. In geology the linking up of the pictures is the prerogative of the stratigrapher. For these reasons a book dealing with physiographical processes in the past is almost bound to have a stratigraphical basis and a stratigraphical arrangement of the material.

The nature of the environments under which the successive geological formations of Britain have come into being has been studied by geologists for more than a hundred years, and though there are many points in the interpretation of the data on which diversity of opinion still exists, yet we can now in most cases visualize the general geographical conditions prevailing in each epoch, and this mental image must form the background for our examination of the physical processes that were at work during that period. This *study of processes* is our primary object in this book. It is clear that our knowledge of their behaviour at the present day must always, as far as is possible, provide the key to the interpretation of the past. At the same time the deductions that can be drawn from the geological record often throw new light on the present-day workings of the processes, since the field of observation is thereby greatly extended in time, and reaches to phenomena that by their nature would be

inaccessible, were the study limited to what can be seen in operation to-day.

It is hoped that the book will also be of service to the student of stratigraphy; for a study of the processes that produced and modified the rocks should help him to understand more easily their puzzling distribution and variety. Isolated, each local development of the rocks of a single age has little meaning, but viewed as a definite product of the physiographical processes of that epoch, each more readily falls into its appropriate place in the reconstructed scene.

The Plan adopted. The book is divided into three Parts, which are themselves sub-divided into Sections, the chapters in each section having a common motif:

PART I

Basic Principles

Section I. Principles of Physiography.
Section II. Principles of Stratigraphy.

PART II

The Post-Carboniferous Systems

Section III. Semi-arid Continental Environments.
Section IV. Epeiric Sea Environments.
Section V. The Alpine Orogeny and the Development of the present-day Conditions in Western Europe.

PART III

The Pre-Cambrian and Palæozoic Systems

Section VI. Pre-Cambrian Environments.
Section VII. The Lower Palæozoic Geosyncline and the Caledonian Orogeny.
Section VIII. Epeiric Environments, mainly in lakes, estuaries and deltas.
Section IX. Volcanic Processes.

The chapters forming Part I are intended as an introduction to the principles of physiography and stratigraphy. They are written as a summary rather than as an exposition of these subjects, and are inserted in order that the reader may have before him the basic principles that are involved in those aspects of the interpretation of the geological record which follow in Parts II and III. In order that the introductory chapters may serve as a key or index to the phenomena discussed in the sequel, abundant cross-references have been inserted.

Parts II and III aim at expounding and illustrating the working

of a variety of physiographical processes, some of which are seldom, while others are frequently, exemplified in the geological record. These processes must in each case be considered as an integral part of the physical geography of the period in which they were functioning; and as the geography was continuously changing, the behaviour of a process in any two instances is rarely identical. It is obviously impossible to deal with every case. A stratigraphical ordering of the material has therefore been adopted; and each process is discussed when a formation is reached that appears to illustrate it particularly well. By using this stratigraphical arrangement, the whole environment at the time can be envisaged; and the process in question can be seen on the one hand to result from that environment and its predecessors, and on the other hand to be actively at work modelling the next set of geographical conditions. The advantage gained from this kinetic conception of the functioning of the processes in relation to the stratigraphical history of their environments, outweighs the disadvantages arising from the separation of descriptions of allied processes or of different aspects of the same process.

Though the arrangement in each part is a stratigraphical one, the reader will possibly be surprised to find that the Post-Carboniferous systems are treated in Part II before the Pre-Carboniferous ones have been described. This arrangement has been adopted after considerable thought, on account of the relative simplicity and completeness of the record preserved in our Post-Carboniferous rocks compared with the mutilated and disconnected story that alone can be wrung from the highly disturbed older rocks. The older systems are relegated for this reason to Part III in which a rather different treatment is employed, in the belief that the student armed with the knowledge and experience gained from his study of processes registered in a fairly full and reliable series of records, can better interpret the more obscure and fragmentary chronicles of the earlier periods; and that in the end he should be able to see the relationship between the new and the old.

The only processes that have been accorded a different treatment are those related to vulcanicity. Illustrations of these are scattered throughout the geological record, but there are so many advantages in dealing with them collectively that a separate chapter (XXV) has been devoted to them.

PART I—BASIC PRINCIPLES

I. THE PRINCIPLES OF PHYSIOGRAPHY

CHAPTER II

SUBTERRANEAN OR HYPOGENE PROCESSES OF CHANGE

The Material available for Study.—Though interested in all parts of the earth, the geologist is primarily concerned with the outermost crust, which is formed of mineral aggregates, hard or soft, loose or compact, called "rocks." Rocks are, broadly speaking, either "*igneous*" or "*sedimentary*" in their origin, though either or both may be so affected by subsequent changes that a third class, "*metamorphic*," has been created for their reception.

Igneous rocks have in all cases been solidified from a state of fusion. They are chiefly compact substances, sometimes glassy, but more often crystalline, and occur in masses that are very irregular in shape, though under certain circumstances sheet-like bodies with parallel boundaries are found. Igneous rocks are being formed to-day in the lava-flows and underground reservoirs of volcanoes. Whatever assumption be made as to the origin of the earth, it is undoubtedly true that the first-formed solid crust consisted of igneous material.

The first rain that fell, started the attack on the rocks which has continued ever since. From that day onwards the weathering of the surface has supplied the rivers with their double load of matter in solution and suspension, which when deposited forms *sedimentary rocks*. Three types are recognized. The detrital matter transported mechanically as fragments, ultimately comes to rest either on land or in a lake or in the sea; rocks thus built up of fragments constitute the *clastic* type.[1] A more varied fate awaits the material in solution. Some may be precipitated chemically (*chemical* type), some may be

[1] *Volcanic ashes* (*pyroclastic rocks*) form a link between the igneous and sedimentary groups. In some cases almost indistinguishable from true lavas, they are in others markedly stratified (p. 346), and have been deposited with and in the same manner as ordinary sediments.

Mineral veins are also difficult to classify: they are mainly derived from cooling magmas, but often may be deposited by superficial underground water.

absorbed by plants or animals, and some remains in solution in the ocean. The accumulated remains of animals and plants may also build up sedimentary rocks, such as coal and limestone (*organic* type). It should be noted that *all* organic and some chemical deposits have ultimately derived much of their material from the atmosphere.

The Forces at Work.—The earth's surface is being and has ever been modified by the action of two distinct classes of forces, namely, those *subterranean* or *hypogene* forces that are actuated by the internal energy of the earth [1] and the kinetic energy of its rotation; and those *surface* or *epigene* forces that derive their energy from the sun, from the rotation of the earth, and from gravity.

Direct Physiographical Effects of Hypogene Forces: Earth-movements and Volcanoes

The main surface manifestations of the internal forces are earth-movements (*diastrophism* [2]) and volcanic activity (*vulcanicity*). These are closely related phenomena and often accompany one another; in fact it is difficult to see how any large-scale movement of the crust can take place without a corresponding transference of molten or potentially molten magma within its deeper parts, and vice versa. The connections between the types of movement and types of igneous activity will be dealt with in the sequel, pp. 16, 355.

The most important conception in relation to hypogene changes is the theory of *isostasy*,[3] which states that in all parts of the earth's surface where equilibrium obtains, equal mass must underlie equal areas. Thus a continental block, in that its general surface-level is far above that of the average ocean-floor, must consist of lighter acidic material (sial) than the supposed basaltic crust underlying the oceans (sima) (Fig. 1). Otherwise the two could not be in stable equilibrium. Similarly large mountain-ranges must overlie areas where the lighter crustal substance projects farther down than normally into the heavier sima. The loading of the crust by, for example, the deposits of a large delta (pp. 322–5), or by the growth of an ice-sheet (p. 236), must tend to cause depression, while unloading by erosion of mountain-chains must tend to produce further

[1] Due partly to radio-activity.

[2] Diastrophism produces effects on the crust to which the term "tectonic" is applied.

[3] J. Barrell, "Strength of the Earth's Crust," *Journ. Geol.*, vol. xxii, 1915; also *Amer. Journ. Sci.*, vol. xlviii, 1919, pp. 281–338. Symposium on isostasy in *Bull. Geol. Soc. Amer.*, vol. xxxiii, 1922, pp. 273–410. J. F. Hayford, *The Figure of the Earth and Isostasy*, 1919.

upward movement. Isostatic compensation supplies the obvious motive force in many cases of earth-movement, and may be the primary cause of almost all diastrophism.[1]

The stratigraphical record makes it clear that the hypogene forces have acted with varying intensity at different times. There are *orocratic* [2] periods of profound and world-wide earth-movements, accompanied by vast volcanic activity (e.g. Siluro-Devonian, Carbo-Permian, Tertiary). These are separated by intervals (*pediocratic* periods) in which these phenomena are greatly in abeyance (e.g. Cambrian, Mesozoic). During each orocratic period the face of the globe has undergone stupendous changes in its relief as the direct

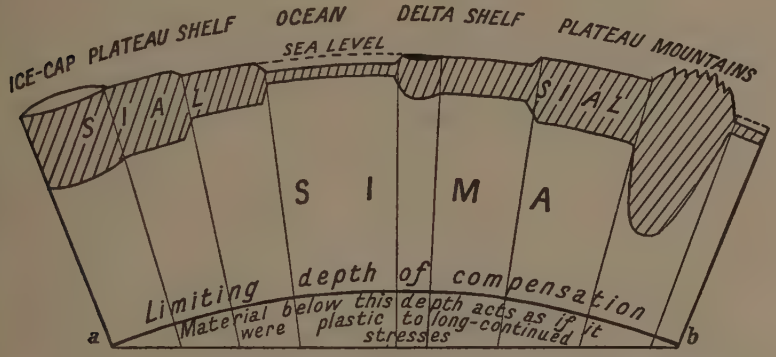


FIG. 1.—The conditions of isostatic equilibrium in the earth's crust. Based on W. Bowie and A. Wegener.

The columns of rock overlying equal areas of the surface of compensation *a*, *b*, must have equal mass to obtain isostatic equilibrium; they have different volumes and densities; the longer the column the lower the density. The continents (Sial) float on the Sima, and the higher the land, the deeper the block of Sial.

result of hypogene causes. The slow-acting epigene agencies have, it is true, operated concurrently and more energetically than during the intervals of quiescence. But even in the pediocratic periods, the non-spectacular phenomena of erosion and deposition, and the ordered changes in the life of the world, given the requisite length of time, produce equally profound modifications in its physiography. Slowly the earth is prepared for the travail of the next orogeny.

Progress through the ages seems thus to have been rhythmical, and to have consisted of intimately interwoven cycles of earth-movement, of vulcanicity, of erosion and sedimentation, and even of organic evolution.

Joly has suggested that the major rhythms are due to the alternate

[1] See especially J. Joly, *Phil. Mag.*, ser. 6, vol. xlv, Nos. 270, 271, 1923.
[2] See Wilhelm Ramsay, *Geol. Mag.*, 1924, pp. 152–163. J. Joly, *op. cit.*

freezing and melting of the basaltic substratum (sima) which underlies both oceans and continents. The evolution of heat from radioactive minerals is, he claims, sufficient, if stored up in the crust, to melt the basaltic substratum, thereby causing differences of density that would inevitably lead to isostatic alterations in the relative heights of continents and ocean-basins (particularly sinkings and submergences of the continents), to expansion in area of the ocean-floors with injection of magma to compensate for this, and to other phenomena. Convection currents would however arise in the liquid basalt and quickly dissipate the stored-up heat, so that freezing would now occur, affecting again the relative heights of continent and ocean and tending to produce emergence. Crumpling of the crust would also occur as contraction set in.

Earth-Movements.—These may be classed as follows:

i. *Epeirogenic* or continent-building: (*a*) Eustatic; (*b*) Isostatic.

ii. *Orogenic* or mountain-building: (*a*) Compressional; (*b*) Elevational; (*c*) Tensional. .

The epeirogenic are slow vertical movements affecting large regions, whereas the orogenic types usually act tangentially, are more violent, and at the same time more local.

i. Epeirogenic.

(*a*) *Eustatic.*—A uniform apparent uplift or depression of the land may be due to the sinking or rising respectively of the level of the sea. Alterations in the shape of the earth and of the ocean-floor or variation in the volume of the ocean-waters [1] must be looked to as the ultimate cause of such changes of sea-level. But though there is interconnection between all the oceans a world-wide uniform change of sea-level cannot be expected, because isostatic or orogenic movements are likely to occur simultaneously with it.[2]

(*b*) *Isostatic* [3] movements, on the other hand, are slow but widespread elevations or depressions of the crust itself, relative to the mean sphere-level of the earth. Their most obvious effect, as shown in the rocks, is the gentle warping or tilting of once-horizontal strata ; but recent epeirogenic movements are naturally best appreciated along a coast line, where their effects can be gauged against a relatively stable reference-line in the shape of the level of the sea. Such movements are evidenced at the present day by strand-lines and beaches now elevated far above the reach of the waves (Fig. 103, p. 237),

[1] As, for example, when enormous volumes of water were abstracted by the growth of ice-sheets on land during the Glacial Period. R. A. Daly, *Amer. Journ. Sci.*, Ser. 4, vol. xxx, 1910, pp. 297–308.

[2] E. Haug, *Traité*, chap. 18. C. Depéret, *Comptes rendus Acad. Sci.*, 1918–1922.

[3] So called because the movements are regarded as explicable by the theory of isostasy explained on p. 6.

and by submerged forests and drowned valleys, etc. The outline of shelving coastlines is easily modified by a change in the relative level of sea and land: a ragged outline results from submergence of subaerial topography; whereas, owing to the usual uniformity of contouring on the sea-floor, elevation generally produces a smooth one.

In the stratigraphical record we find proof that epeirogenic movements have gone on continuously throughout geological time. The most convincing piece of evidence is the existence of enormous thicknesses of similar rock. These are sometimes coastal, sometimes open-sea deposits, but in either case the nature of the sediments show that they were deposited throughout under a fairly uniform depth of water. This feature implies a long-continued subsidence of the sea-floor that in general kept pace with the accumulation of sediment (pp. 169, 265 and Figs. 112, 140, Pl. I. B).

A widespread *unconformity* (see p. 64) may also witness to epeirogenic movement; for if marine deposits are found to lie upon the worn-down and bevelled edges of older rocks, it is clear that a land-surface degraded by erosion has been invaded by the sea.

Yet another type of earth-movement has been suggested and particularly championed by Alfred Wegener.[1] This is the supposed displacement and drift of the continental masses which, it is claimed, has taken, and is taking place, as a result of geophysical causes. The theory is bound up with that of isostasy. Wegener's *continental-drift theory* envisages the oceans as underlain by a sima that behaves as a viscous fluid; and the continents as blocks of sial, floating like icebergs in the sima, and tending to drift gradually westwards and equatorwards. It claims that the drifting can account for a number of the earth's major physical features, such as mountain-ranges, rift-valleys, island-festoons, etc. It also helps to explain remarkable differences of climate that can be shown by the geological record to have prevailed in one locality at different times (Fig. 37) and also the anomalous geographical distribution exhibited by many plants and animals both at the present and in the past; but from our present point of view it is particularly important as suggesting one of the possible causes of orogenic movements and vulcanicity (Fig. 78, p. 181). The theory, however, is far from being universally accepted.

ii. Orogenic.

These movements are at any one particular time limited to definite belts of the earth's surface, which in certain cases may extend over many degrees of arc.

[1] A. Wegener, *Die Entstehung der Kontinente und Ozeane*, Brunswick, 1915; and English translation by J. G. A. Skerl, London, 1924; also J. W. Köppen and A. Wegener, *Die Klimate der Geologischen Vorzeit*, Berlin, 1920.

(*a*) The *compressional type* is perhaps the best known. It is found in all the big, so-called *folded* mountain-chains, such as the Alps

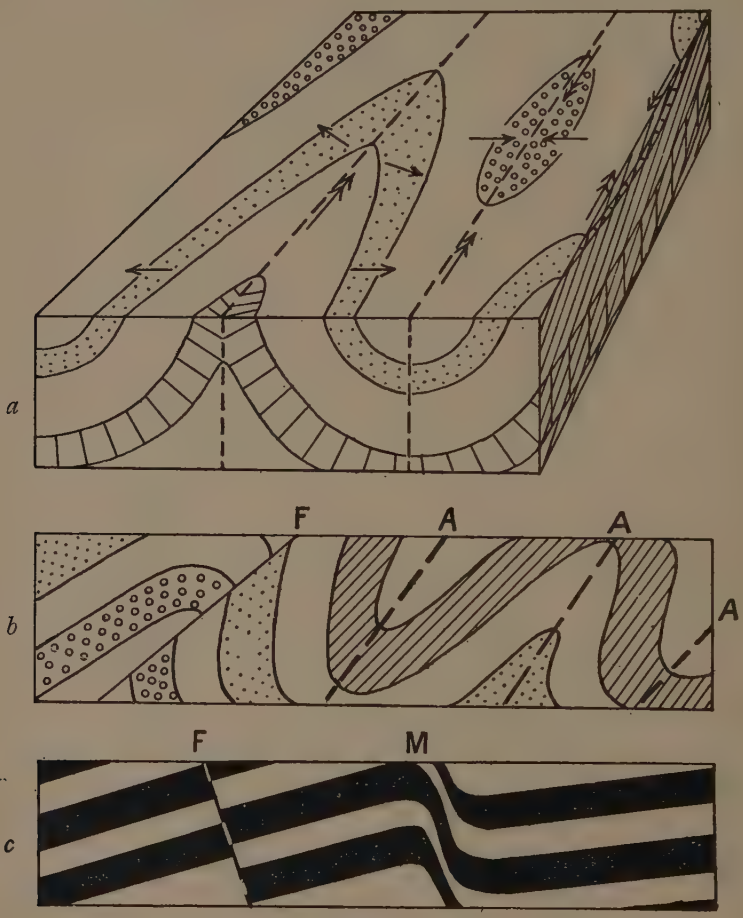


FIG. 2.

a. Denuded symmetrical anticlines and synclines, axial planes (broken lines and right side of the block) are vertical. Two-barbed arrows show the pitch of the folds; single barbed, the dip.

b. Unsymmetrical folds and overfolds, axial planes (A) inclined to the vertical. F, reversed fault.

c. Diagram-section showing F, normal fault; M, monoclinal fold.

(p. 174), Appalachians and Himalayas. Here the rocks are usually the victims of a *lateral thrust* which has thrown them into folds, overfolds, and recumbent folds, and broken them by faults and thrusts

(Fig. 2, *a* and *b*). The chains produced are usually arranged as a series of arcs, as may be well seen in the Swiss Alps and the Carpathians. The convex side of the arc indicates the quarter to which the surface-thrust was directed (pp. 178–9, Fig. 75).

Perhaps the most remarkable feature about the great fold-mountains, is the fact that they have almost invariably been located on the sites of former zones of crustal down-warping (geosynclines, p. 258 and Fig. 111), where during preceding epochs great thicknesses of strata had been accumulating.[1]

The really big orogenic movements have always profoundly revolutionized the geography of the earth, not only by raising up a belt of mighty mountain-chains, where once had lain the sea, but by inducing a less intense crustal folding and dislocation outside that belt. Not only so: the movements and the accompanying changes in the shape of the ocean-floor have led to profound alterations in the distribution of land and water. The indirect effects of all this on the climate and life of the earth can well be imagined. In fact, the events of each orocratic period (p. 7) gave to biological evolution a stimulus the importance of which is gradually becoming more and more recognized.

(*b*) *The elevational type.*—Evidence is accumulating to show that direct *vertical uplift* has been an important factor in the elevation of some parts of the Rockies and Andes;[2] and according to Joly all big mountain-chains owe their height to isostatic uplift, even though their structure results from lateral compression.[3]

(*c*) *Tensional type.*—Under tension,[4] the crust tends to crack into blocks that may move up or down, or sideways [5] relatively to one another. The blocks are usually separated by normal faults along which movement has taken place, but sometimes the subsidence of a block is effected by a monoclinal fold (Fig. 2, *c*). Differential elevation of a block relative to its surroundings may produce a *plateau* or a *block-mountain*. Such is the origin of the Basin Ranges of Nevada

[1] J. W. Evans, Pres. Address Geol. Soc., *Proc. Geol. Soc.*, vol. lxxxii, 1926, p. lx. E. Haug, *Traité de Geol.*, vol. i, chap. xii.

[2] R. T. Chamberlin, "The Building of the Colorado Rockies," *Jour. Geol.*, vol. xxvii, 1919, pp. 145, 225, and *ibid.*, vol. xxix, 1921, p. 166. J. A. Douglas, *Q.J.G.S.*, vol. lxxvi, 1920, p. 1, and vol. lxxvii, 1921, p. 246. W. Penck, *Abh. Sachs. Akad. Wiss. Math.-Nat. Kl.*, vol. xxxvii, 1920, p. 420. T. O. Bosworth, *Geol.* and *Palæont. of N.W. Peru*, London, 1922. J. Joly, *op. cit.*, p. 13.

[3] See also R. D. Oldham, "The Support of the Mountains of Central Asia," *Rec. Geol. Surv.*, India, xlix, 1918, with references.

[4] J. W. Evans, Pres. Address Geol. Soc., *Proc. Geol. Soc.*, vol. lxxxi, 1925, p. lxxx. J. W. Gregory, *Geology and Rift Valleys of East Africa*, 1921. E. Krenkel, *Bruchzonen Ost-Afrikas*, 1922.

[5] If torsion also acts.

and Utah (Fig. 3).[1] Where the movement has taken place recently

FIG. 3.—Block-mountains, after W. M. Davis.

(Reprinted by permission from *Physical Geography*, by W. M. Davis, published by Ginn & Co., Ltd.)

the line of fracture may still be represented by a *fault-scarp*, i.e. a scarp or bluff produced by the actual elevation or depression of the crust along the fault. If, however, denudation has proceeded far, and if the rocks brought into contact with one another by the fault are more or less equally resistant to erosion, the boundary of the block may be marked by no topographical feature. Where erosion has laid bare in the elevated block far older and harder rocks than those forming the surface in the adjacent depressed areas, the block will on account of its hardness form hills or mountains projecting above their surroundings. It is then termed a "*horst*" (Figs. 4 and 5).

FIG. 4.—Map of the Rhine-Graben; floored by Tertiary and Pleistocene, and bounded by faults. Full black, Hercynian Horsts. Horizontal shading, Mesozoic.

Rift-valleys or *Graben* are formed when narrow elongated blocks have sunk down; they are bounded by fault-scarps. The Rhine valley, dropped down between the ancient horsts of the Vosges and the Black Forest, is a European example; the Jordan valley, the Red Sea basin, and the great African Rift valleys are similar structures. So also is the central valley of Scotland (p. 281, Fig 127).

[1] G. K. Gilbert, "Studies in Basin-Range Structure," *U.S. Geol. Surv. Prof. Paper* 153, 1928.

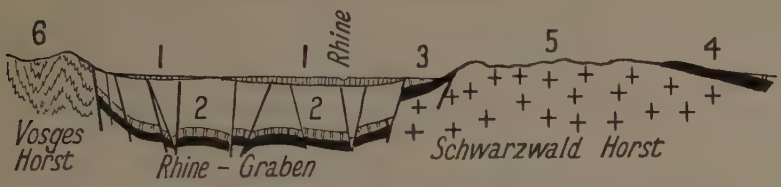


FIG. 5.—Section across the horsts of the Vosges and Schwarzwald, and the intervening Rhine-Graben. Underground structure proved by borings.

1, Rhine alluvium and gravels. 2, Oligocene. 3, Jurassic. 4, Triassic. 5, Granite (Pre-Triassic). 6, Lower Carboniferous.

Vulcanicity.

The term vulcanicity can be used to cover not only the surface manifestations of molten igneous magma as seen in volcanoes, but its deep-seated activities in plutonic and hypabyssal intrusions.

Volcanoes [1] can be classed into:

FIG. 6.—Fujiyama from Iwafuchidai. (From a photo.)

1. Central-Vent Volcanoes, with more or less circular feeders and conical shapes. They may be composed of ashes or lava or of a mixture of both (composite cones). (*a*) *Ash* and (*b*) *Composite* cones usually have steep sides and a central crater that is generally deep, but

[1] For illustrations of recent volcanoes, see Tempest Anderson, *Volcanic Studies in Many Lands*, London, 1903.

not very large in proportion to the size of the whole cone. Examples (*a*) Monte Nuovo near Naples, (*b*) Vesuvius, Krakatoa, Fujiyama (Fig. 6). *Lava-cones*, on the other hand, are built mainly of lava-flows. The largest examples (Fig. 7) are composed of very fluid

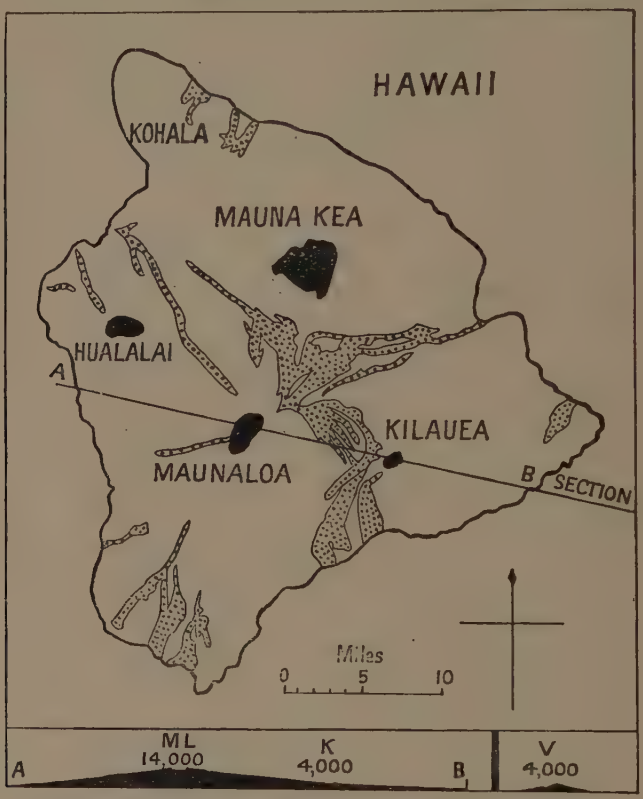


FIG. 7.—Island of Hawaii, adapted from H. S. Washington.

Sinks or Calderas, black. Historic lava-flows, stippled. Comparative sections: A B, across Mauna Loa and Kilauea; and V, across Vesuvius.

lavas (basalts) which, instead of the familiar slopes of Vesuvius or Fujiyama, give rise to flat cones with wide steep-walled craters, known as calderas. The island of Hawaii is a volcanic pile of this type, with gentle slopes rising to over 13,000 feet above the sea. The island is, however, only the summit of a far vaster submarine portion that descends to the ocean-floor at a depth of 20,000 feet. At present there are two active volcanoes in the island, which pursue independent courses, and are apparently fed from independent reser-

voirs of magma. The Cainozoic volcano of Mull forms a good British example (p. 358 and Pl. II).

The intrusions connected with central-vent volcanoes have either a radial or concentric arrangement around the focus of activity (Fig. 9, *c*).

2. Fissure-Volcanoes, in which lava wells up along a crack that may be a fault or a joint. Often a series of small vents is found

FIG. 8.—Laki or Skaptár Fissure Volcano, looking along part of the line of small craters that follow a fissure some 12 miles long.

The plains seen in the background have been built of lava issuing from the fissure, as can be seen toward the right. The scoria cones rarely rise more than 300 feet above the plain. (From a photo by Tempest Anderson.)

aligned along the fissure (Fig. 8). Vast areas may be buried by the flows from such fissures, and gradually lava-plateaux are built up. One of the largest volcanic regions of this type is the Snake River Plateau of Idaho, but probably the Icelandic examples are the best known (pp. 352, 355).

When dissected by erosion lava-plateaux are found to be built up of a number of flows interleaved with intrusive sills and sheets, and cut through by subparallel vertical dykes, some of which no doubt represent the igneous matter that solidified in the actual

feeders of the later vents. In some regions a series of such parallel dykes traverse country in which they are the sole witness of volcanic activity, and, indirectly, of the tensional stress to which it has been subjected (see p. 354, Figs. 147, 148).

Volcanoes modify the crust by transferring material from below to the surface, and thus building up volcanic cones or plateaux. On the other hand they may by explosive eruptions destroy their own handiwork. Amongst the important functions of volcanoes must be reckoned the supply to the atmosphere of carbon dioxide gas derived from the igneous magmas. This gas is being continually abstracted from the air by plants and animals (p. 22), for whose existence it is necessary. Vast quantities of carbon dioxide have been more or less permanently locked up in the shape of coal, oil, and limestone, and had not the supply been replenished by volcanic emanations, life would long ago have become impossible.[1]

There is an intimate relationship between the type of volcano and the type of earth-movement with which it is associated. This statement applies also, but less obviously, to the type of magma. Thus in the deep isostatic depressions known as geosynclines (p. 268, Fig. 109) it is usual to find submarine volcanoes and spilitic lavas (Spilitic suite); in folded mountains and in the adjacent regions, central-vent volcanoes with andesitic lavas and other calcic rocks (Pacific suite); and in regions of tension and large vertical movements fissure-volcanoes with alkaline rocks (Atlantic suite), often of basaltic types.[2]

Igneous intrusions at shallow depths are known as *hypabyssal*, whereas deep-seated ones are called *plutonic* or *abyssal*.
Hypabyssal intrusions include:

Dykes—vertical, parallel-sided, wall-like bodies (Fig. 9, *a*, *c*, 147, Pl. II, 14).

Sills—parallel-sided bodies with upper and lower surfaces generally conformable to the bedding of the rocks into which they are intruded (Fig. 9, *b*).

Sheets—more or less parallel-sided bodies, lying fairly horizontally or moderately inclined, transgressive to the structures in which they occur (Figs. 9, *a*, *c*).

Laccolites—roughly bun-shaped bodies, conformable to the structures in which they occur, but apparently arching up those which overlie them (Figs. 9, *b*). May be multiple (cedar-tree laccolites).

[1] W. Warth, *Geol. Mag.*, 1915, pp. 158, 159.
[2] A. Harker, *Q.J.G.S.*, vol. lxxiii, 1917, pp. lxvii–xcvi.

Plutonic or Abyssal intrusions include:

Batholiths[1]—enormous masses having more or less vertical transgressive boundaries, usually found in folded mountain-ranges (Figs. 9 *d*, 127).

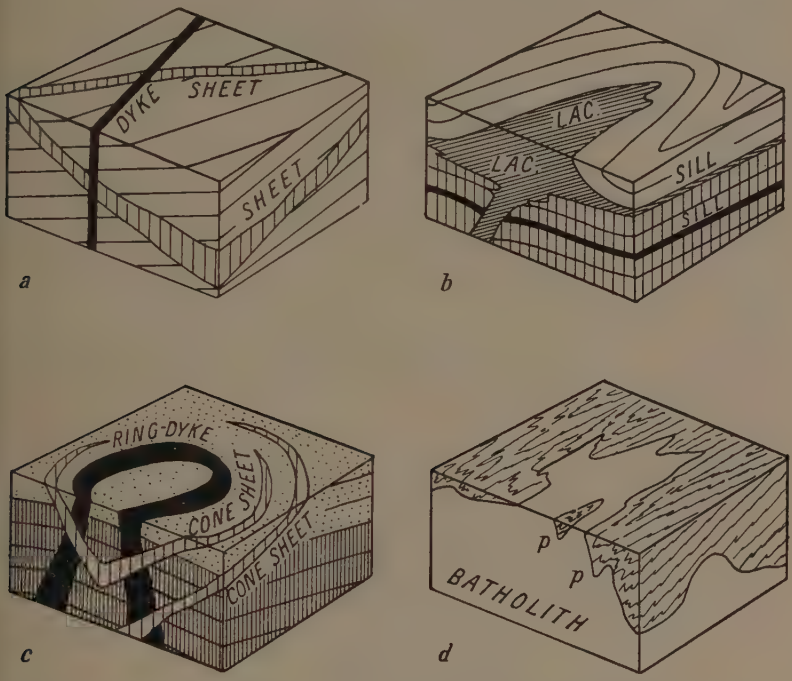


FIG. 9.—Forms of Intrusions.

a, Dyke and sheet cutting inclined strata. *b*, Laccolite (LAC) and sills, showing arching of overlying strata. *c*, Ring-dyke and cone-sheets. *d*, Batholith with cross-cutting relation to folded rocks (after Daly). *p*, Roof-pendant.

Stocks and Bosses—similar to batholiths, but much smaller (Fig. 144 *d*, p. 348).

Laccolites—plutonic masses with gently sloping upper surfaces: in some cases demonstrably similar (but on a larger scale) to hypabyssal laccolites (Fig. 150, p. 357).

Earthquakes.

The vibrations of the ground which we call earthquakes, are waves set up in the crust by the sudden underground relief of some earth-stress. Two types are recognized:

[1] R. A. Daly, *Origin of Igneous Rocks*, London, 1914, pp. 185–190. Also consult chap. ix, in which he discusses the relationship between batholithic injection and mountain-building.

(*a*) **Volcanic Earthquakes** are apparently connected with underground explosions or with the disrupting of the rocks by the volcanic forces, as they rend their way through towards the surface. Volcanic earthquakes may be very destructive, but their effects are usually local. Example: Ischian Earthquake of 1883.

(*b*) **Tectonic Earthquakes**[1] are caused by orogenic movements, and originate when a sudden slip takes place along a fault-plane or when a submarine landslip occurs. They are commonly felt over much greater areas than the volcanic quakes. Examples: San Francisco, 1906; Indian, 1897; Tokyo, 1923.

We are not here concerned with the surface phenomena accompanying earthquakes. Indeed, for our present purpose an earthquake can be regarded simply as a manifestation, perceptible to our senses, of the unseen forces of vulcanicity and orogenesis. For the sedimentary record of earthquakes in British rocks,[2] see p. 339.

Metamorphism.[3]

Another direct effect of the hypogene forces is found in the changes that are produced in rocks when they are subjected either to great heat or to great pressure, or both. A rock is said to be *metamorphic* when it has had its original minerals more or less completely recrystallized or changed into other minerals.[4] Frequently such changes are accompanied by the development of new textures and the obliteration of the original structures. Metamorphic changes are a function of the following factors: the nature of the original rock, the temperature, pressure and mechanical deformation to which it has been subjected, and the presence or absence of water and mineralizing solutions. As may be seen from the diagram (Fig. 10) which illustrates the cycle of changes in rocks, metamorphic changes are of two types.

(*a*) The term **contact** or **thermal metamorphism** is reserved for changes that occur as a result of the invasion of a rock by a hot magma. Its effects are local, and directly related to the shape and

[1] C. Davison, *Origin of Earthquakes*, 1912, *Manual of Seismology*, 1921, "The Japanese Earthquake of 1923," *Geogr. Journ.*, vol. lxv, 1925. C. E. Dutton, *Earthquakes in the Light of the New Seismology*, 1904. G. W. Walker, *Modern Seismology*, 1913. R. D. Oldham, various papers in *Q.J.G.S.* C. G. Knott, *Physics of Earthquake Phenomena*, Oxford, 1908, and *Proc. Roy. Soc. Edinburgh*, vol. xxxix, 1919. B. Galitzin, *Vorlesungen über Seismometrie*, 1912.

[2] See also E. B. Bailey, L. W. Collet and R. M. Field, "Palæozoic Submarine Earthquakes near Quebec City," *Journ. Geol.*, vol. xxxvi, 1928, pp. 577–614.

[3] C. R. Van Hise, *A Treatise on Metamorphism, U.S. Geol. Surv. Monograph* 47, 1904. C. K. Leith, *Structural Geology*, London, 1914. G. W. Tyrrell, *Principles of Petrology*, Part III, London, 1926.

[4] Thus excluding cases of change due to metasomatism (p. 25) and weathering (p. 23).

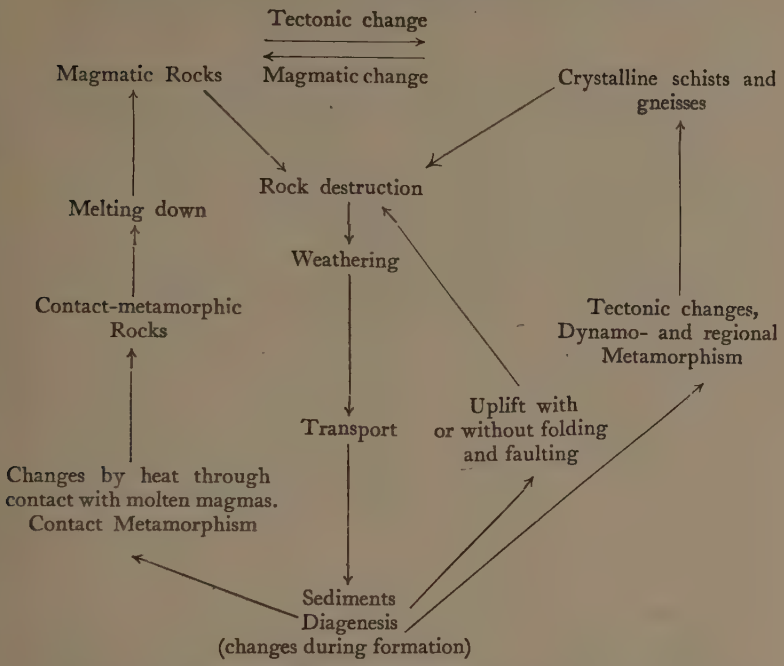


FIG. 10.—The Cycle of Rock-Changes, after H. Cloos and L. Kober.

The arrows pointing downwards refer to surface, exogenetic or epigene processes; those pointing upwards to subterranean, endogenetic or hypogene ones.

size of the invading mass. In extreme cases the heat may actually fuse the rocks and in this way produce new magma (Fig. 10). Molecular rearrangement and recrystallization of the mineral substances are the most conspicuous features. Where mineralizing vapours and solutions abound, not only rearrangement but additions to the mineral content of the original rock are effected (pneumatolysis). The formation of quartz-veins and metalliferous veins may be closely associated with this phenomenon.

(*b*) **Regional** or **Dynamo-metamorphism** has taken place over large tracts, perhaps especially under geosynclines where rocks have been depressed into the hotter zones of the crust, and have there been subjected not only to high temperatures but also to deformation. Hence we find that rocks that have undergone such a metamorphism are characterized by special arrangements of the recrystallized and newly-developed minerals to form distinctive textures (e.g., granulitic, foliated). Here again in extreme cases melting may take place, and new magma comes into being to start the cycle afresh (Fig. 10).

Indirect Physiographical Effects of Hypogene Forces: Directional Effects on Drainage-lines

Crustal deformations largely determine the directions of the drainage of a country in two ways: Firstly the initial directions followed by the rivers are often the result of the manner in which the region has been elevated. Thus a dome-structure may produce a radial arrangement of the rivers (p. 201).

Occasionally obstructional effects occur, as when a valley-floor is elevated with sufficient rapidity to dam back the stream; [1] or when subsidence produces a lake (e.g., many of the Swiss lakes [2]) or alters the outlet of a pre-existing lake (e.g., the Great Lakes of North America[3]).

In the second place under the influence of deformation and erosion, rocks of varying resistance to denudation are brought to the surface. The agents of erosion are in this way guided by the geological structure of the country. All the intricacies of the development of a drainage basin as a rule result from an inter-play of these two factors (see p. 198).

Various other Indirect Effects.—Through movements of elevation and depression, barriers appear and disappear, producing effects on the distribution of climate, of ocean currents, and of plants and animals. Through these agencies also, the rate of erosion by rivers and glaciers is largely determined (pp. 240–1).

[1] This rarely occurs except where a sudden rise takes place, as with the dislocations which cause earthquakes.

[2] See A. Heim, *Geol. der Schweiz*, vol. i, pp. 399–415.

[3] A detailed account is found in F. Leveret and F. B. Taylor, *U.S. Geol. Surv. Monograph*, liii, 1915.

CHAPTER III

SURFACE OR EPIGENE PROCESSES OF CHANGE: DENUDATION

As already pointed out, the surface of the earth and the life on it are continually being affected by agencies, like the atmosphere and wind, rivers and glaciers, and the sea, that derive their energy mostly from the sun. The atmosphere and water in one of its forms are involved more or less directly in all these so-called *epigene* processes of change.

The sun's differential heating of the various regions of the earth, and of the air in contact with them, is the prime cause of the circulation of the atmosphere; and thus of the winds and to a large extent of the ocean-currents also. The direction of the winds and currents is, however, influenced by the spin of the earth (kinetic energy). The direct heating by the sun, the distribution of land, water and ice, and the directions of prevailing winds and currents, govern the nature of the climate. This in turn regulates the type of life, and type of erosion and deposition that is to be found in any particular region.

The air can hold a variable amount of moisture in the form of vapour, the quantity being governed by the temperature and pressure. "Dry" air passing over a sheet of water causes some of the latter to evaporate and become invisible water-vapour. When the temperature falls below a certain point this vapour is readily given up again as mist, rain, hail or snow. Some of the moisture thus precipitated falls directly into the sea and some gradually finds its way as streams, rivers and glaciers back to the ocean [1] or into inland lakes.[2] Thus a cycle is completed which controls nearly all the phenomena of denudation and deposition, by which the rocky crust is shaped after it has been moulded by the hypogene forces outlined in Chap. II.

Composition and Functions of the Air.—The composition

[1] Moving water or ice derives its power to move and so to do work from the forces of gravity.

[2] Some water during this process is lost directly by evaporation back into the air, and a certain amount is locked up in the rocks, but the major part behaves as outlined.

of air, omitting water and the constituents that are present only in diminutive quantities, is given by Mill [1] as follows:

	By weight.	By volume.
Nitrogen	76·03	78·21 or 4/5
Oxygen	23·14	20·96 or 1/5
Argon	0·77	0·79 or 1/125
Carbon dioxide	0·06	0·04 or 1/2500
Total	100·00	100·00

Air, however, always contains in addition a variable amount of water-vapour.

Nitrogen [2] and Argon are inert gases; but Oxygen and Carbon dioxide enter readily into chemical combinations, and are of great importance in the epigene changes. They are soluble in water, and in nature it is in solution that they generally function, water entering into many of the reactions. Each may be considered from the point of view of its effects on living organisms, and on the rocks.

In the respiration of both plants and animals some of the tissues are burnt by combination with the oxygen of the air. It is this reaction that provides the energy requisite for the vital processes. The product of the combustion is carbon dioxide that passes out into the air. Plants have the power, when energized by the sun's rays, of breaking up the carbon dioxide of the atmosphere. Oxygen is liberated, while the carbon in combination with water is converted into organic substances that form the tissues and food of the plant, and thus indirectly of animals. Accumulations of dead animal and vegetable matter give rise to peat, coals and oil, which are thus ultimately a product of the atmosphere. Carbon dioxide has also a less direct influence on organisms, which is of particular interest to the geologist: dissolved in water it forms a weak acid that attacks carbonates and other minerals, forming soluble compounds of which calcium bicarbonate is especially important. This substance is one of those absorbed by plants and animals that build calcareous skeletons, the remains of which may accumulate to form new deposits of limestone. In such rocks there are therefore stores of oxygen and carbon that have ultimately been derived from the gases of the atmosphere through the agencies of organisms (p. 16).

The effects of oxygen and carbon dioxide on the rocks is dealt with under weathering and metasomatism (p. 25).

[1] H. R. Mill, *Realm of Nature*, 2nd Edition, 1913, p. 107. A useful summary of the properties of these different substances is given on pp. 106–115.

[2] Essential to plant and animal life, but chiefly abstracted from the atmosphere through the life-processes of bacteria.

The Part played by Air and Water in the Processes of Denudation and Deposition.[1]

(a) The processes of denudation or erosion are those that tend to destroy and level off the surface of the solid crust, both on land and below the sea. They may be classified under three headings:

(1) *Weathering* . . .	chemical.
	mechanical.
(2) *Transportation* . .	chemical, in solution.
	mechanical, in suspension.
(3) *Corrasion* . . .	chemical.
	mechanical.

Under the heading of *weathering* are included all processes that chemically dissolve or disintegrate, or mechanically break up already-formed minerals and rocks. Weathering reduces the surface of the land to a state in which its constituents are available for disposal by the agents of *transportation* (Fig. 10), such as gravity, wind, running water or creeping glacier. Part of the load carried by running water is borne invisibly in solution, and part visibly in colloidal solution and in suspension. Under suitable conditions the rock-fragments, as they are transported, grind away or *corrade* the surfaces over or against which they are moving.

(b) The process of deposition which is complementary to that of denudation may be effected by (1) mechanical, (2) chemical, (3) organic agencies. The material denuded from the land comes to rest in a variety of ways to form new sedimentary rocks. Since these are laid down one above the other in layers, lens-shaped or sheet-like in accordance with the circumstances governing their deposition, they are often spoken of as *stratified* rocks, each layer being termed a *stratum* or *bed*. According to their resting-place, such deposits may be classed as *terrestrial, lacustrine, fluviatile, estuarine*, or *marine*. In the physiography of the present, erosion is the most conspicuous and obvious phenomenon, but its direct effects are only occasionally observable in the rocks constituting the stratigraphical record here: deposition is more in evidence. A thorough understanding of both erosion and deposition is therefore a most necessary part of the mental equipment of both geologist and geographer.

[1] R. D. Salisbury, *Physiography*. C. A. Cotton, *Geomorphology of New Zealand*. C. A. Geikie, *Textbook of Geology*, Part II. P. Lake and R. H. Rastall, *Textbook of Geology*.

Denudation or Erosion.

Climatic Control.—Since the processes of denudation vary with the environment under which they act, those relating to :

(*a*) *terrestrial erosion* will be classified with reference to climatic control, as—

(1) *Humid*,[1] where the rainfall is abundant, or fairly evenly distributed throughout the year. Forest or parkland is usually the natural vegetation (p. 229).

(2) *Dry*,[2] where the rainfall is deficient or seasonal. These areas are usually either deserts or natural grass-lands (savannas and steppes). Monsoon-lands fall partly in this and partly in the preceding class (pp. 26, 83, 325).

(3) *Glacial*,[3] where the temperature is low enough to prevent the winter's snowfall from disappearing in summer. These areas are cold deserts; some are very wet at certain seasons when the snow melts (*Tundras*), others on or near the great ice-sheets have a low precipitation throughout the year. Glacial conditions are found in mountains at higher and higher levels as the equator is approached. In the Bolivian Andes on the equator, the snowline occurs at 18,500 feet on the dry and 16,000 feet on the wet side of the mountains.

(*b*) Under *marine* [4] conditions erosive processes go on without so much reference to the type of climate.

i. Humid Climates

(a) **Weathering.**—The mechanical fracture of solid rocks is not so pronounced in humid climates as it is in more arid regions where there are rapid diurnal changes of temperature producing differential expansion and contraction with a consequent disintegration of the surface rocks; but it does occur. Where the water in the rocks is liable to alternate freezing and thawing, the expansion of water on freezing is a potent disrupting force. The roots of plants and the activities of burrowing animals like rabbits, worms, ants and solitary bees also assist the process of comminution. The nature of the jointing in the rocks exercises an important influence on the processes outlined.

[1] W. M. Davis, *Geographical Essays*, chaps. xiii, xiv, xviii.

[2] W. M. Davis, *Physical Geography*, chap. xv. J. Walther, *Das Gesetz der Wüstenbildung*, 4th Ed., Leipzig, 1924. S. Passarge, *Die Kalahari*, Berlin, 1904.

[3] W. H. Hobbs, *Characteristics of Existing Glaciers*. W. M. Davis, *Geographical Essays*, chaps. xxiii. and xxiv.

[4] A. Geikie, *Textbook of Geol.*, vol. i, pp. 556–578, with references.

Where there is sufficient precipitation the chemical attack on the rocks is more important than the mechanical. Rain-water contains free oxygen and carbonic acid in solution (see p. 22) to which other acids are added during its passage through the soil to become ground-water (Fig. 11). Thus armed, water in the pores and cracks of the surface-rocks (zone of weathering) can dissolve out the soluble parts, leaving behind only the disintegrated insoluble residue. Or it may enter into various chemical combinations (oxidation, hydration, carbonation, etc.) with the minerals in the

FIG. 11.—Present-day Weathering of Mount Sorrel Granite. Compare Fig. 45. (From photo by Bosworth.)

rock. The resultant new minerals are frequently less resistant to weathering than the original ones. The reactions also usually involve changes in volume, whereby the rock becomes disrupted, and more porous and permeable, thus facilitating the further attack by water and air. In both cases weak solutions are formed (calcium bicarbonate, calcium sulphate, sodium carbonate and chloride, magnesium chloride, iron bicarbonate, silicic acid, etc.). These either emerge as spring-water to feed the rivers, or travelling downwards into the zone of *permanent saturation* help to cement the rocks of that zone and to bring about *metasomatic* changes in them, that is to say chemical changes produced by interaction between the original minerals in the rock and the percolating solutions. Thus magnesium salts may interact with limestone ($CaCO_3$) and form dolomite ($CaMg(CO_3)_2$).

In moist hot climates weathering goes on to great depths, especially if the soil is protected by vegetation from being rapidly washed away. Peculiar aluminous and ferruginous soils, known as *Bauxite* and *Laterite*, are the product of weathering and metasomatism in tropical regions where wet and dry seasons alternate (e.g., the Monsoon-lands) [1] (p. 208).

(b) **Transportation.**—The greater part of the transportation of weathered material towards the sea is effected by running water. Moving screes, landslips, and soil-creep help the rainwash to keep the rivers supplied with their load of detritus, but the roots of vegetation tend to hinder this action. Part of the material that reaches the streams is rolled along the bottom, and part is carried in suspension; while there is always the invisible load in solution, varying in amount and composition with the nature of the drainage-basin. In colder regions floating ice in spring or summer may carry larger stones down-stream than could normally be transported.

There are very definite laws governing the mechanical transportation by running water.[2] The carrying capacity of a river varies directly with its volume, but the maximum size of particles transported is proportional to the sixth power of the velocity of the current. The latter factor determines the preciseness with which river-borne detritus is graded according to the size and weight of the particles (pp. 118, 304). Increase in volume, as in a flood, greatly increases the velocity. Therefore rivers in flood are competent to deal not only with more, but with far larger fragments than are moved by their normal currents. This accounts for the destructiveness of floods.

If the velocity of a fully loaded stream is checked, for instance, on the inside-curves of meanders, or when it enters a lake or a flat part of its course, or when it spreads out over a flooded alluvial plain, the loss of velocity leads to deposition of part of its mechanically carried load. The larger particles sink first, and then the finer. On entering the sea a more complete deposition takes place than on entering a lake, because the colloidal clay-matter carried in suspension is rapidly precipitated by the salt water [3] acting as an electrolyte.

It follows from the laws given above that in nearly all rivers transportation is going on in some parts concurrently with deposition

[1] For a good summary and bibliography, see C. S. Fox, "Bauxite and Aluminous Laterite," *Mem. Geol. Surv. India*, vol. xlix, pt. 1, 1923, p. 287.

[2] See especially G. K. Gilbert, "Geology of the Henry Mountains," Report 2, *U.S.G.S.*, 1887, chap. v.

[3] J. Johnstone, *Oceanography*, p. 72.

in others, the two processes tending towards the formation of the even grade of a true plain.

(c) **Corrasion.**—*Chemical corrasion* may be said to be effected when water in passing over soluble rock, like limestone or rock salt, dissolves it bodily.

Mechanical corrasion is the tearing away and grinding away of the bed of a stream, and the attrition and comminution of the particles that are being transported. Generally speaking, a stream becomes a corrading agent when it is supplied with tools in the shape of pebbles, sand, and mud, and when it possesses more energy than is required for transportation alone.

In rivers with sufficient velocity the channel is excavated deeper by continual scour of pebbles and sand, especially where local irregularities lead to swirls that gyrate the material, and produce pot-holes. This is termed *downward corrasion* and is best displayed in rapids, gorges, and waterfalls. When a river has reduced the slope of its channel (the thalweg), over part of its course to a certain minimum gradient, depending on the size, velocity and load of the stream, downward corrasion almost ceases on that reach, which is then said to be *graded* (p. 240). Eventually the whole river may reach this condition. The graded state results when the current velocity is so low that under normal conditions the river is only able to carry forward its load. Any further reduction of gradient or increase of load would lead to deposition. Hence it can corrade no lower. But it is still capable of *lateral corrasion*; i.e. the scouring and undercutting of its banks on the convex side of meanders, and the consequent widening of the valley-floor and over-steepening of its sides. Sooner or later by landslips, by rainwash, by corrasion of tributaries, and by various other factors, this steepness is reduced and the general lowering of the drainage area is gradually accomplished (pp. 202–6).

Planation.—The end-product of these processes is a *plain* or *peneplain*, the making of which involves not only the erosion of the hills, but the filling in of the low-lying portions, where the streams lose their velocity and render up their load. Coastal erosion by waves and tidal currents assists in the process.

It requires enormous lapses of time for such planations to come to pass. The vast length of time covered by the stratigraphical record is emphasized by the fact that many are known (pp. 198–9).

ii. Dry Climates

(a) **Weathering.**—Here the mechanical breaking up of the surface by temperature-changes and by frost predominates. In

hot deserts there is a great diurnal range of temperature, and the resultant expansion and contraction at the surface disrupt even the most compact rocks, which either shiver into small fragments or peel off in flakes (exfoliation). In cold deserts, comminution is effected chiefly by frost-action. In both types, giant scree-deposits are found burying the lower slopes of the hills (pp. 86, 110, 301 and Figs. 12 and 44).

FIG. 12.—The Granite Dome of Djebel-Kassala. (From a photo by Walther.)
The granite is weathering by exfoliation, and the foot of the mountain is covered with angular scree and blocks, with here and there rounded knobs of granite.

Chemical weathering is in abeyance in deserts, being almost absent under glacial conditions, but recognizable in hot arid places. Solution and redeposition is here chiefly brought about by dew or by the ground-water as it passes by capillary attraction to the surface (p. 122).

(b) **Transportation.**—This is effected by gravity, wind, and streams. Expansion and contraction actuated by temperature-changes causes the gradual creep of the screes to lower levels. Wind is, however, the most potent force. The finer fragments are caught up by it and blown away to form sand-dunes and dust-deposits (loess). The vast stony deserts (e.g. the Libyan Hamada) (Fig. 13), swept free of sand and dust, are the most solemn witnesses in almost every arid region to the reality of wind-transport (known sometimes as *deflation*). But the deserts are not absolutely rainless, and many dry regions enjoy a seasonal rainfall. When the rain

does come, it is often torrential. The rock-debris unprotected by vegetation may be swept away by a raging flood where a few hours previously no trickle could be seen and where a few hours later a dry bed will again be found. These more or less temporary streams may soon throw down their load of angular stones, sand, and mud, as the waters spread out on flatter ground or sink into the parched soil. Hence dry flat-bottomed gulleys (wadies) mark upland courses of the streams, while temporary lakes (playas), dried lake-bottoms and delta-fans are other typical features of a desert landscape (pp. 83-6, 116, 121, Fig. 33).

FIG. 13.—The Libyan Hamada between Keneh and Khargeh. (From a photo by Walther.)

(c) **Corrasion.**—The natural sand-blast of wind-driven particles is perhaps the most effective corrasive force in arid and semi-arid regions. The action is not limited to a channel as in the case of a river or glacier. The greatest effect, however, is seen on the low parts of upstanding obstacles, which become carved into curious monumental land-forms (Fig. 45). The sand-blast due to a prevalent wind may cut knife-edge ridges on the desert floor (Fig. 14) and shape loose pebbles into *dreikanter*, that is, elongated stones with three keel-like ridges running along their lengths (pp. 116, 225). The sand employed for the sand-blast is itself reduced to rounded grains (p. 113).

Streams and rivers, when they occur in deserts, exercise similar corrasive effects as in a normal climate; but when a large river, deriving its water from elsewhere, traverses a desert (e.g. the Colorado across the desert of Arizona, and the Nile across the Egyptian desert), or when a torrent develops from a storm, transportation and corrasion by the water are so infinitely more active in the main river-channels than in the tributaries and over the neighbouring country, that the

former are quickly excavated below the general level of their surroundings and form steep-sided valleys known as *canyons*, *wadies*, *spruits*, etc.

FIG. 14.—Wind-cut Hill near Negritos, Peru, seen from the lee side, showing summit, keel and part of the tail. Prevalent wind coming towards the observer. (From a photo by Bosworth.)

Planation.—Though the agencies of denudation in deserts are in part different from those of normal climates, nevertheless they are claimed by some to be competent, given time enough, to reduce the country to a state of low relief.[1] The base-level of erosion may here be that of an inland-sea or salt-lake which may be either above or far below sea-level. Some authorities hold that unless there be some such body of standing water, there is no limit to downward erosion by the wind; but Walther points out that the presence of underground water acts similarly in a limiting capacity, in that the presence of the damp surface automatically puts an end to deflation when in the course of erosion the ground-water level is reached. Not only so, but the damp surface may actually cause deposition by arresting wind-blown sand and dust (pp. 101, 103).

[1] J. Walther, *Das Gesetz der Wüstenbildung*, 4th edit., 1924. W. M. Davis, *Geographical Essays*, XV, "Geographical Cycle in an Arid Climate," pp. 296–322, and esp. pp. 306–309. Quotes Passarge, *Die Kalahari*, Berlin, 1904. A. C. Lawson, "Epigene Profile of the Desert," *Univ. California, Publ. Bull. Dept. Geol.*, vol. ix, 1915, pp. 23–48.

iii. Glacial Climates

(a) **Weathering.**—This is mainly effected by frost where the country is bare of ice; while under ice-sheets and glaciers the rocks are ground to rock-flour or torn up in blocks by the passage of the ice. The absence of chemical weathering is characteristic.

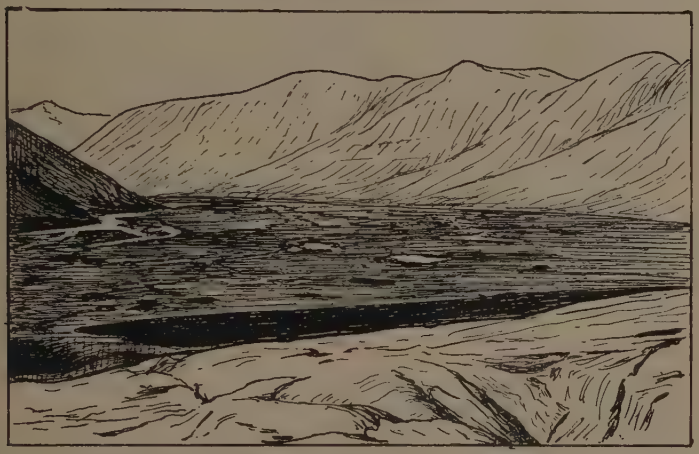


Fig. 15.—Outwash Fan of Hidden Glacier, Alaska, with braided streams and kettlehole-pits.

Dark object at the foot of the glacier (foreground) is a great ditch or fosse with a lakelet in it, that drained out through the moraine-covered ice forming the near part of the outwash fan. (From a photo by R. S. Tarr.)

(b) **Transportation.**—This is likewise for the most part effected by movements of the soil, and of valley-glaciers and ice-sheets.[1] Unlike a river, moving ice is able to transport throughout its course and side by side fragments of all sizes, which may be carried on it or in it. Not only so, but ice can be driven uphill, carrying its load of boulders, gravel, sand, and clay to points actually higher than the sources from which they were derived (p. 216).

In addition to transportation by the ice, at certain seasons glacial rivers become of importance as carrying agents. They may run on, in, or under the ice; and as they are generally rapid and sometimes confined to narrow channels, their carrying power is often considerable. Moraines formed by the material melted out of the glaciers may be re-sorted and re-arranged by streams issuing from the ice-front (Fig. 15). The deposits of a glacial region are

[1] These differ in dimensions and other characteristics, see W. H. Hobbs, *Characteristics of Existing Glaciers*, pp. 7, 8.

therefore usually a mixture of formations originating directly from the ice (glacial), with others laid down by the melt-waters acting as rivers (fluvio-glacial) (p. 217). The region adjoining a glacial one is also indirectly affected, for its rivers in spring and summer may receive melt-water floods which, like those of semi-arid regions, have enormous carrying power and are likewise equally abundantly supplied with detritus (p. 231).

(c) **Corrasion.**—Snow and stagnant ice act as protective agents to the surfaces they cover; but a moving glacier shod with stones and sand plucked from its bed is a most efficient rasp, becoming the more effective the thicker the ice and the greater the consequent

FIG. 16.—Mountainous District undergoing glaciation. After W. M. Davis.

pressure below it. In this connection we must realize that, unlike a river-channel which is but a narrow strip along the valley-bottom, the whole valley-floor is the channel of the glacier.[1] This is excavated in accordance with the law of the *adjustment of cross-sections* formulated by Penck for glaciers and rivers. He states that a glacier or a stream tends to adjust the size of every cross-section of its channel to suit the volume of ice or water that must pass through it. Big glaciers must therefore have deep channels, which on the disappearance of the ice we call glaciated valleys. It follows that in a once-glaciated district the side-valleys, being the former channels of small glaciers whose flow was obstructed by the main glacier, are shallower than the trunk-valleys (Figs. 16 and 17). Such tributaries are

[1] A. Penck, "Glacial Features in the Surface of the Alps," *Journ. Geol.*, vol. xiii, 1905, pp. 1–19, and *Verhand. d. viii Internat. Geog. Kongress*, Berlin, 1900.

termed "hanging valleys" because they lie far above the level of the trunk-valley and their streams have to cascade down its sides to join the main river (p. 214).

FIG. 17.—The same district as in Fig. 16 after disappearance of the ice. After W. M. Davis.

Figs. 16 and 17. Reprinted by permission from *Textbook of Geology*, Part I, by Pirsson and Schuchert, published by John Wiley and Sons.

Owing to the effects of constrictions and of differences in rock-resistance on the cutting power of the glacier, its thalweg is not as a rule a smooth curve, but on the disappearance of the ice is seen to fall in steps or to be interrupted by hollows in which lakes frequently occur (Fig. 18). Other characteristics of glaciated valleys that declare the corrasive activity of moving ice (Fig. 17) are U-shaped cross-sections, the truncation of spurs between lateral valleys, steep-sided valley-heads (cirques, cwms, corries), rounded hummocks (roches moutonnées), and smoothed, striated and grooved surfaces (pp. 211–14).

The features just described are typically the work of valley-glaciers in mountainous regions, and are said by Davis to be signs that the glaciers that produced them were in their youth or early maturity. Little, however, is known about the cycle of erosion under glacial conditions.[1]

An *ice-sheet* differs from a valley-glacier in covering a far greater proportion of the region in which it lies. Its corrasive effects are therefore found over hills and valleys alike. The vast territories

[1] See W. M. Davis, *Geograph. Essays*, XXIV, espec. pp. 658–662, and *Q.J.G.S.*, vol. lxv, 1909, pp. 281–350.

in once-glaciated regions now mantled over by thick moraines of clay and stones form the most convincing proof of the ability of an

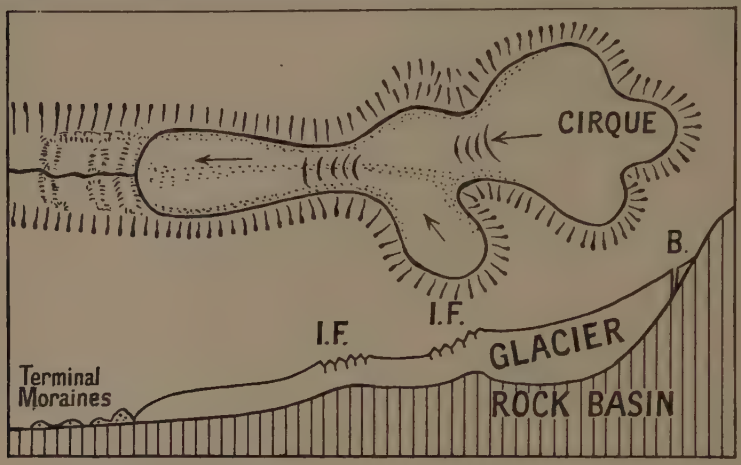


FIG. 18.—Diagram-plan and section of a Valley-glacier to show the stepped bottom of the valley, with rock-basin below the cirque.

I.F., Ice-falls; B., Bergschrund.

ice-sheet to act as an enormous rasp. Corrasion, however, also takes place by means of sub-glacial streams which, supplied with

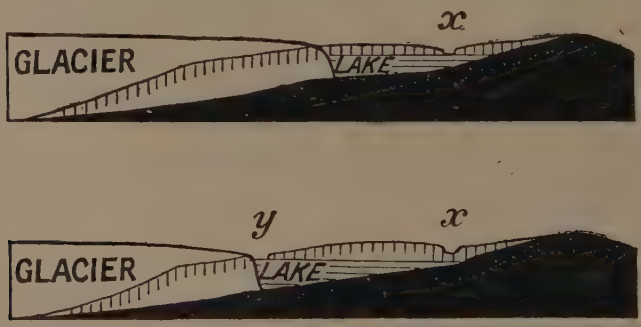


FIG. 19.—Diagrams of glacially-dammed Lake with *x*, an overflow channel at the first stage, and *y*, a marginal channel at the second stage.

Solid black, the outline of the valley-floor. Horizontal shading, the lake water. Vertical shading, the outline of the valley-side across which the water escaped. Based on H. B. Maufe, in Kendall and Wroot.

abundant detritus, may erode remarkable sub-glacial gorges and pot-holes ("giant's kettles"), while the melt-waters from the margin

of the ice may excavate deep and wide channels (overflow channels, p. 226 and Fig. 19, *x*, *marginal channels, Urströmtäler*).[1] Sometimes the marginal channels are cut by a stream flowing between the ice and rising ground, and on the disappearance of the ice have only one side remaining (Fig. 19, *y*). During the melting and retreat of former ice-sheets, the abundance of thaw-waters rendered the contemporary stream-erosion particularly effective, even outside the actual glaciated area (p. 231).

iv. Marine Erosion

(a) **Weathering.**—The rocks under the sea are protected from weathering by the water. Any changes brought about by their contact with the sea-water are due to metasomatism rather than to weathering in the restricted sense of the word (p. 99).

(b) **Transportation.**—Waves and tidal currents are responsible for the movement of coastal detritus; and great rivers (like the Amazon) produce light freshwater currents that carry river-borne material far out to sea. Drifts and ocean-currents are less important agents for the transporting of detritus, but they are largely responsible for the dispersal of floating animals and plants, the hard parts of which contribute towards the sediments on the ocean-floor when the organisms die. Where confined by land to narrow channels (as, for instance, the Gulf Stream between Florida and Cuba),[2] currents are stated to sweep the ocean-bed clean of all sediment to great depths (pp. 137–40, 162).

(c) **Corrasion.**—The battering of the coast by waves and wave-driven shingle tends to undercut cliffs and to grind off a shelving platform. Angular stones and coarse sand are rounded in this process; but the finer grades (below 0·8 mm. diameter) are left angular in contrast to similar products of the desert (see p. 113). The compression and release of air in joints by the rising and falling of the tide and by battering waves, also levers off masses from rocky cliffs and so helps the general erosion of the coast line.

The success of the attack by the waves depends to a great extent on the hardness of the rocks, so that on an exposed coast, headlands

[1] K. Keilhack, *Jahrb. Preuss. Geol. Landesanst*, Bds. xix, xxxii. F. Wahnschaffe, *Oberflächengestaltung d. norddeutschen Flachlandes*, 3rd Edit., 1909, and *Geol. Charakterbilder*, Heft 19, 1913. E. Geinitz, "Das Quatär Nordeuropas," *Lethara geognostica* III, 2. I, p. 317. P. F. Kendall, *Q.J.G.S.*, vol. lviii., 1902, pp. 401–568. F. W. Harmer, *Q.J.G.S.*, vol. lxiii, 1907, p. 470.

[2] The maximum velocity of the Gulf Stream is stated to be 220 km. per diem, i.e. greater than that of the Rhine at Coblenz. See L. J. Henderson, *Fitness of the Environment*, Macmillan, 1913, p. 182.

and bays usually correspond with resistant and soft rocks respectively. It is also influenced by the ready removal of the coastal detritus by currents. Under favourable circumstances, the sea may produce a wide and very level submarine platform even in hard rocks (pp. 94, 257). The levelness is due to the small vertical range within which the waves are effective as corrasive agents (Fig. 20).

FIG. 20.—Elevated Marine Platform. Pembrokeshire coast.

Land-Sculpture.—The Geographical Cycle under Humid Conditions.

It must be recalled that the epigene agents of denudation work on surfaces moulded by the hypogene forces (p. 20), and that the latter frequently interfere with the progress of the work. But left to themselves, the epigene processes aim at the production of a peneplain, that is to say, a gently-rolling lowland, the original irregularities of which have been largely obliterated by the double process of cutting and filling. Such a peneplain would rise so gradually from sea-level that to the eye it would be sensibly flat, and in a typical case it would be continued seawards across the continental shelf as a submarine plain. Though not conforming to the last point, the uplifted peneplain that stretches from the folded ranges of the Cape Province northward to the Congo basin on the west and to the Abyssinian highlands on the east, may be cited as a good example.

The production of a peneplain is the latest phase in a "geographical

cycle" that begins when [1] an uplift either initiates new land and new drainage-lines on it or "rejuvenates" a pre-existing drainage-system (p. 240). The early part of the cycle (Fig. 21 A), when the rivers are "young," is characterized by rapidly increasing topographical relief as the streams entrench themselves. As the drainage-system becomes more *mature* (Fig. 21 B), a stage marked by the

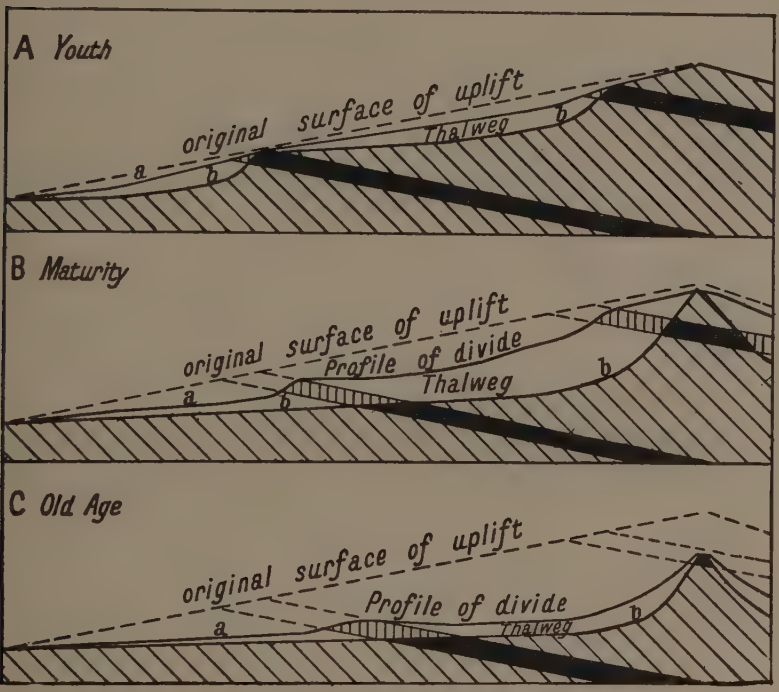


FIG. 21.—Diagram to show the relation of Surface Relief to the stages in a Cycle of Erosion.

The dotted line in all figures represents the initial slope of a tilted plain. The continuous line (*a*), below it, outlines the profile of the divide, and the distance of this line from the thalweg (*b*) is the measure of the amount of relief. Compare the profile of the thalweg with that in Fig. 18.

strongest relief and the greatest variety of form is attained. From here onwards through later maturity, at first fairly rapidly and then slowly, the diversity of land-form and the amount of relief decreases. Finally in the old age of the system, erosion checks itself (Fig. 21 C); for it tends to produce a very low relief which so far reduces the activity of the erosive agencies that deposition over all the lower

[1] See W. M. Davis, *Geograph. Essays*, XIII, pp. 249–295.

parts of the basin is perhaps the most conspicuous feature of the old-age phase, in which a new peneplain is achieved. For this to come about, it is essential that the level of the sea, which determines the base-level of the river-systems, should remain constant; but such a cycle requires so vast a length of time that earth-movement generally supervenes before its completion.

The major geographical cycles therefore tend to be initiated by the major geological upheavals (see Chap. II); they are complicated by subsequent earth-movements; and their final stages can only be attained in the epochs of greatest crust-stability (p. 167).

Under normal climatic conditions, the so-called "laws of land-sculpture" formulated by Gilbert[1] control peneplanation. These "laws" cover (*a*) the influence of the velocity and volume of rivers (p. 26); (*b*) the tendency of divides to be permanent, though their position shifts towards the less-active drainage-system until equal declivities are attained on the two sides of the divide; and (*c*) the influence of the varying resistance to erosion offered by rocks.

The tracing out of the development of present-day drainage-systems with reference to their geological antecedents, forms a fascinating branch of geomorphology. Some examples are dealt with in the sequel (pp. 198, 222).

[1] G. K. Gilbert, "Report on the Geology of the Henry Mountains," *U.S. Geol. Surv. Rep.* 2, 1877, chap. v.

CHAPTER IV

SURFACE OR EPIGENE PROCESSES OF CHANGE (*cont.*): DEPOSITION

An understanding of the way in which new sedimentary rocks can originate from the material rendered available by the processes of erosion is the most important key to the interpretation of the stratigraphical record. It can only be dealt with in outline here.[1]

The three methods of formation of strata, through *mechanical*, *organic*, and *chemical* agencies, have already been mentioned (p. 23).

I. The mechanically-formed deposits are built up from fragments of pre-existing rocks. They are therefore often termed *clastic* (e.g. conglomerates, breccias, sandstones, clays, boulder-clays, etc.). Typically they are made from detritus derived from the erosion of the land, and carried to its resting-place by winds, rivers or glaciers, or transported by marine currents;[2] but the group includes rocks, such as coral-muds, coral-sands, shell-sands and bone-beds, composed essentially of broken bits of the hard parts of organisms; and it may be extended to include *tuffs* and *volcanic ashes* (*pyroclastic rocks*) (p. 5).

II. Organically-formed deposits are in the main the direct outcome of living organisms, though naturally they grade by admixture of detritus into the clastic group. Three sub-groups may be recognized:

(*a*) *Carbonaceous.*—This embraces accumulations of vegetable matter, such as peats, lignites, coals, and cannels, which by admixture with mineral detritus may grade into oil-shales and carbonaceous shales (Chap. XXIV). Mineral oils and natural gas result from the decomposition of organic material, but can hardly be termed rocks.

(*b*) *Skeletal.*—The hard parts secreted by plants and animals may accumulate on such a scale as to build up new rocks (e.g. calcareous

[1] The reader is referred to the following: A. W. Grabau, *Principles of Stratigraphy*, 1913. W. H. Twenhofen, *Treatise on Sedimentation.* C. Lyell, *Principles of Geology.* H. C. Sorby, *Q.J.G.S.*, vol. lxiv, 1908, pp. 171–233, and *Presidential Address to Geol. Soc.*, 1879. Papers by J. Barrell, E. M. Kindle, E. Blackwelder, E. W. Shaw, T. W. Vaughan, in *Bull. Geol. Soc. America*, vol. xxviii, 1917.

[2] de Lapparent calculates that the detritus obtained by subærial erosion and brought to the sea is thirty-three times the amount produced by marine coast-erosion.

skeletons of algæ, foraminifera, corals (pp. 148, 164), etc., making lime-stones; siliceous skeletons of diatoms, sponges, and radiolaria, forming siliceous oozes which consolidate as cherts (p. 268).

(*c*) *Catalytic.*—Bacteria and algæ appear to be able to cause the precipitation of lime and iron salts in water, e.g. some calcareous and ferruginous oolites (pp. 137, 148), and bog-iron ores.

III. Chemically-formed deposits.—The various salts held in solution in the water of rivers, lakes, salt-lakes, and the ocean, are liable in varying degrees to be chemically precipitated either through *the intervention of organisms*, as just stated, or *by chemical reactions* with other salts (p. 252); or by the solutions becoming *supersaturated through evaporation* (pp. 43, 164). The physico-chemical control [1] and the part played by organisms are not yet thoroughly elucidated.

Control by the Environment.

The *methods* of *accumulation* just outlined operate under a variety of *environments* which form the basis of a further classification as follows:

I. Continental:	II. Marine:
(*a*) Terrestrial.	(*a*) Neritic { Littoral and Estuarine. Shallow-sea.
(*b*) Fluviatile.	(*b*) Bathyal or Deep-sea.
(*c*) Lacustrine.	(*c*) Abyssal.

I. Continental Deposits

Under a continental regime there is a very distinct climatic control over the types of deposit formed. For example, regions of abundant rainfall and with free drainage to the ocean contrast markedly with those with meagre precipitation and an internal drainage-system or with those with a glacial climate.

Mechanically-formed Continental Deposits

(a) Terrestrial.

(1) *Residual.*—Soils, dirt-beds, bauxite, laterite, talus, and screes are residues left behind in the process of weathering: they may occur at their point of origin or be re-sorted and re-deposited (p. 353 and pp. 86, 101, 154).

(2) *Æolian or Wind-formed.*—Sand-dunes, and loess or dust-deposits. In these deposits there is a very perfect grading by size

[1] R. H. Rastall, *Physico-chemical Geology*, London, 1927.

and weight of the grains, which are often rounded. Sand-dunes move in the direction of the prevalent winds by the transference of sand-grains from the windward to the leeward side of the dune, where they come to rest as a result of eddies that check the velocity and therefore the carrying power of the wind (Fig. 22). This results in strong diagonal bedding (p. 113, Fig. 48). Such sands are usually unfossiliferous. Loess, on the other hand, has no bedding, but strongly-developed vertical joints: it may contain terrestrial fossils. Æolian deposits may occur at any level (p. 233).

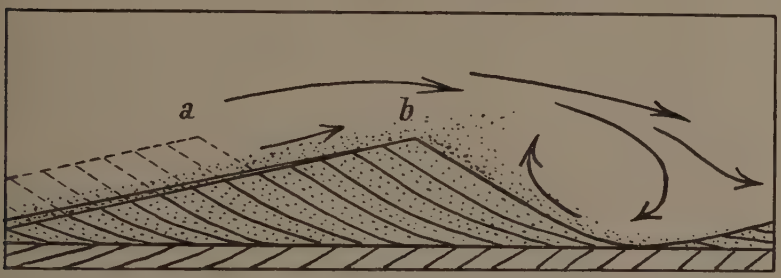


FIG. 22.—Diagram of an advancing Sand-dune.

The broken lines indicate the parts of the beds that have been destroyed in the advance from crest-position *a* to crest-position *b*. The dune is shown crossing a wind-eroded surface of a second dune deposited by a current from another direction.

(3) *Glacial.*—Moraines, gravel- and sand-mounds, and boulder-clay. The material deposited is often unweathered and usually very poorly sorted, so that large stones may even lie embedded in clay. The deposits may occur at any level, and are often unstratified and usually unfossiliferous (pp. 215–9). Individual deposits are frequently small, local, and directly related to an ice-front (p. 218).

(4) *Volcanic.*—Tuffs, ashes and agglomerates. The material is sometimes well graded, but near vents there is usually an admixture of large blocks in the finer ash. The deposits are highly irregular when formed on land. Usually unfossiliferous (p. 350).

(b) **Fluviatile.**—Rivers deposit gravel, sand and mud in parts of their channels (bars, banks) and on the neighbouring land during floods (alluvial plains, and alluvial cones and fans) (pp. 115, 296). Such deposits are likely to be local and lenticular and to exhibit contemporaneous erosion (p. 337, Fig. 139) and they may pass insensibly into estuarine and deltaic accumulations. The fossils are either freshwater or terrestrial forms.

(c) **Lacustrine.**—On entering a lake a stream throws down much of its load of sediment, the pebbles and coarser sand building

out a delta at the river mouth (Figs. 50, 99), and the finer particles settling as a film of mud over the deeper parts (pp. 302–4). In arid and semi-arid regions the lakes may be temporary or fluctuate greatly in size. In these circumstances a recent deposit may be baked hard and partly broken up before the next layer is carried in by another flood (pp. 86, 114). Lakes may also be the recipients of glacier-carried or wind-borne sediment (pp. 85, 217). Fossils as in (*b*).

Organically-formed Continental Deposits

(a) **Terrestrial and Fluviatile.**—An impressive group of organically-formed rocks embraces the *peats*, *lignites*, *coals* and *anthracites* (p. 327). They are being, and have been in the past, built up of the decaying remains of plants which lived either on the land or in lakes, estuaries and lagoons. Most of these deposits have accumulated on the spot where they are now found (pp. 145, 327), but in others the plant debris has been washed from its place of growth, and has been laid down in lakes, lagoons, and deltas. In peats the vegetable matter is only slightly altered; but in lignites to some extent, and in coals and anthracites to a marked degree, there is a great change in the molecular arrangement of the organic substances of the plants, accompanied by loss of volatile hydrocarbons. In this group, as in clays, the contraction in volume on the drying out and consolidation of the rocks under pressure is enormous. It has been contended that the reduction in thickness "in passing from the state of wet undisturbed peat" to coal "will not be much less than 15 or 20 to 1," though other observers put it at a lower ratio.[1]

(b) **Lacustrine.**—In lakes the siliceous skeletons of minute floating plants (Diatoms) occasionally build up thick deposits of "diatomaceous earth." Calcareous algæ are also instrumental in the formation of freshwater limestones. Lacustrine deposits are known which are almost entirely composed of innumerable shells of a few species of molluscs or crustaceans (shell-marls, *Paludina* limestones, Entomostracan limestone) (p. 154).

Chemically-formed Continental Deposits

(a) **Underground.**—The soluble salts in the ground-water may interact in the zone of permanent saturation with other substances to form new insoluble compounds that either may function as cementing materials, or by replacing part of a rock may give rise to metasomatic changes (as where limestone is converted to dolomite or to chert) (p 98). The precipitation of such minerals as calcite, gypsum,

[1] P. F. Kendall, *Report Brit. Ass.* for 1922, 1923, p. 65.

rock-salt, etc., may take place as impregnations (p. 136) or in veins or as stalactites and stalagmites in caves.

(b) **Fluviatile.**—On the other hand much of the ground-water with its chemical load in solution escapes into the rivers. Some of the salts in solution may then be precipitated as tufa and sinter, directly or indirectly by bacteria and algæ.

(c) **Lacustrine.**—Some rivers drain into internal drainage-basins where inland-seas or salt-lakes store up the soluble salts. It often happens, however, that in these basins evaporation equals or exceeds the inflow,[1] and the solutions are gradually concentrated until the various salts are precipitated from saturated solutions.[2] Tufaceous limestone (e.g. in "Lake Lahontan") (p. 154), fine-textured limestone (pp. 86, 164), dolomite (p. 122), anhydrite and gypsum (p. 99), rock-salt (p. 103), and finally potassium-salts (p. 103) may be thrown down; but the last three, by virtue of their high solubility, only separate out as the water dries up completely. Ancient deposits of this type constitute our most important natural supplies of salts. They have only survived where they have been sealed off by impervious clays which have preserved them from the attack of ground-waters (see pp. 30, 103). Some chemical deposits which may be regarded as sedimentary rocks, as, for instance, the sodium carbonate and borax found in the beds of certain lakes, the Chile saltpetre, the sulphur-muds and siliceous sinter of volcanic regions, are derived from solutions in "juvenile" waters that are expelled from igneous magmas. They therefore grade into vein-deposits, which are for the most part best regarded as the product of igneous activity rather than of epigene agencies.

Summary.

Continental deposits from their mode of origin have somewhat limited lateral extensions, with a striking exception in the case of the loess and some coals, which may cover enormous areas. Extensive too are glacial deposits, taken as a whole; though the individual units composing the broad sheets of glacial "*drift*," both in North America and in Europe, are often remarkably local. The limited lateral extension of most continental formations implies that, compared with marine types, they are lenticular rather than sheet-like strata. They are particularly prone to local and rapid changes in composition from

[1] The Caspian was once part of the sea, but its water is now diluted by reason of the great rivers that enter it, so that it is less saline on the whole than the latter. Certain land-locked bays, however, undergo great evaporation, and here salts are being precipitated; but elsewhere the water is brackish.

[2] See especially J. Walther, *Gesetz der Wüstenbildung*, 4th edit., 1924, chap. xxviii, pp. 192–196.

place to place, and they are also very liable to be partly or completely destroyed by erosion. These are all features that have to be borne in mind when attempting to interpret ancient continental formations (see Chaps. VI–IX, XXIII, XXIV).

II. Marine Deposition

The Salts of the Ocean (*sensu lato*)

The functions of the salts in sea-water [1] in respect to marine deposition may be briefly referred to. The salinity is greatest in the tropics and in land-locked seas, and in these positions the lime salts may be *precipitated* directly or through the intervention of organisms,[2] to form certain oolites and impalpable calcareous oozes.[3] It is round the continents especially that *secretion* of lime and silica by marine organisms is most in evidence, though this goes on to some extent in the surface-layers of all seas. In parts of the ocean where terrigenous matter is absent, the floor may be covered by organic oozes (Pteropod, Foraminiferal, Radiolarian and Diatom), consisting of the calcareous or siliceous skeletons of organisms which, living near the surface, when they die, rain down through the water. In profound ocean depths, however, pressure increases the solubility of carbon dioxide to such an extent that the waters are acid, and the calcareous skeletons pass into solution before they reach the bottom. Those made of aragonite, e.g. Pteropods, are the first to dissolve, at depths exceeding 9,000 feet; then the calcite ones, e.g. Foraminifera, follow suit, below 15,000 feet (p. 164). Siliceous skeletons, however, accumulate at these great depths; but even these may be dissolved in the most abysmal parts, which cover vast regions and are floored by the so-called "Red Clay," which consists of volcanic and meteoric dust alone.

When arms of the sea are cut off by the formation of a bar or by earth-movement, an inland-sea results; and under favourable circumstances salt deposits may be laid down, as in a salt-lake (see p. 103). The original sea-water having a different composition from that of a lake, the resultant deposits differ in composition and in their relative quantities.

[1] For chemistry and physics of sea-water, see J. Johnstone, *Introduction to Oceanography*, chaps. vi and vii. For composition of sea-water, see A. W. Grabau, *Principles of Stratigraphy*, pp. 145–54, F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv. Bull.* 770, 1924, pp. 122–133.

[2] J. Johnstone, *op. cit.*, p. 87, for details of the function of bacteria, etc.

[3] A. W. Grabau, *Principles of Stratigraphy*, pp. 674–7, 996. W. A. Tarr, *Geol. Mag.*, 1925, pp. 259–63 with bibliography. A. R. Daly, *Bull. Geol. Soc. America*, vol. xx, 1909, pp. 155–70.

Detritus in the Ocean (*sensu lato*)

In suspension in the ocean-waters hang mineral and organic particles. The mineral detritus is derived from the land by subaerial and coastal erosion, and from the sea-floor by wave- and current-action. Some is also of volcanic origin. The organic material is dealt with on p. 47.

As a rule the larger particles in marine sediments are less well-rounded than in wind-deposits.[1] The finer are partly fragments of pre-existing minerals and partly colloidal clay-substances.[2] Though the particles settle much more rapidly in salt water than in fresh, their actual deposition can only take place below the so-called *wave-base*,[3] i.e. the depth at which material of any particular grade ceases to be agitated and kept in suspension by wave- or current-motions. By this means a fairly perfect grading according to the volume and density of the particles is effected in marine sediments. They do not however equal æolian deposits in this respect. The coarser material is limited to coastal regions, except in so far as it may be rafted out into the open ocean either by its own buoyancy (e.g. pumice) or by floating ice or vegetation. Even the finer particles, as a rule, settle within 250 miles of the land, except opposite the mouths of giant rivers like the Amazon, Congo, and Ganges, which set up freshwater surface-currents (see above) that carry terrigenous material to 600 or 1,000 miles from land. Elsewhere the ocean-abysses are generally almost free from terrigenous detritus.

Subdivisions of the Ocean (*sensu lato*)

The ocean, in the broad sense of the word, can, from a geological standpoint, be subdivided into *Oceans* and *Seas* (*sensu stricto*) (Fig. 23).

The oceans are those parts of the hydrosphere in which the general level of the sea-bed lies far below the mean level of the floor of the seas that cover portions of the continental blocks. Some authors hold that there is a fundamental difference between the rock substance constituting the continental blocks and that underlying the ocean-depths; and that on geophysical grounds there is no possibility of the ocean-bed becoming a continental area, or vice versa. Whether this view be correct or not, it is certainly true that, with possible trifling exceptions (see p. 55), there have not been recognized amongst strata

[1] Some marine sands consist of wind-rounded grains that have been blown into the sea. Wind-borne dust is also found as a constituent of marine deposits at all depths.

[2] Johnstone, *op. cit.*, p. 72.

[3] J. Barrell, *Bull. Geol. Soc. Amer.*, vol. xxviii, 1917, pp. 778–782.

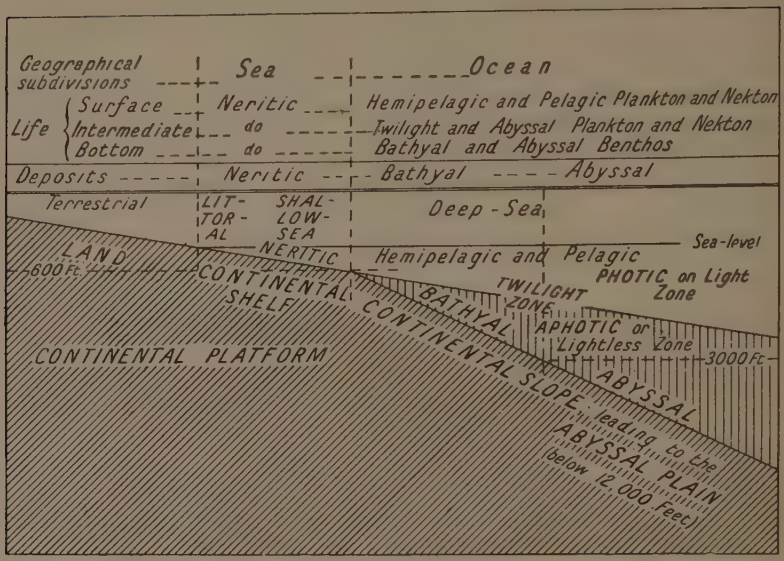


FIG. 23.—Diagram showing various Subdivisions of the Earth's Surface from the point of view of the distribution of life and of deposits.

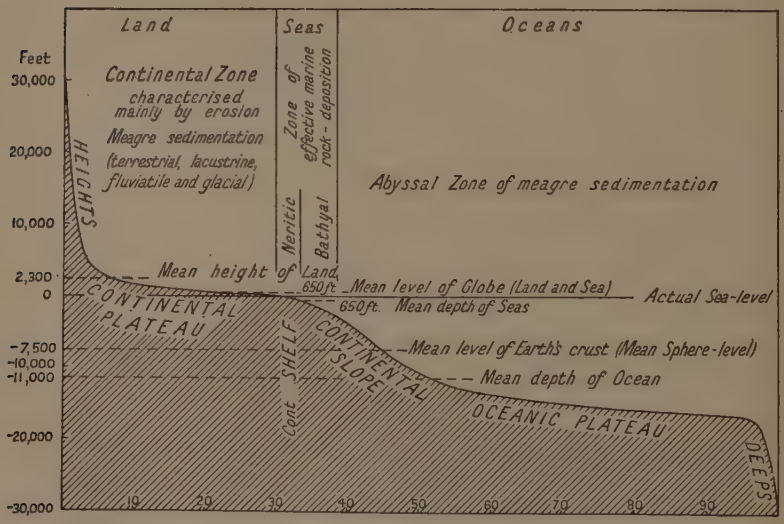


FIG. 24.—Diagram showing the Proportions of the Earth's Surface characterized by Erosion, and by effective and defective Sedimentation, and their relation to the contouring of the Globe. (Based on H. Wagner.)

forming the continents, deposits that can be matched with those known to be now accumulating in the ocean-abysses (p. 55).

The term **sea** is restricted to those parts of the hydrosphere which form the borders and extensions of the oceans, or which directly overlie portions of the continents. Seas have always been the principal *locus* of sedimentation; and consequently a knowledge of the conditions prevailing in them is of vital importance to the geologist. Fig. 24 shows that at present only about 10 per cent of the earth's surface is covered by seas.

Seas may be classified as follows:[1]

(1) **Epeiric or Continental seas**, overlying submerged parts of continents.

(*a*) *Shelf seas*, 0–600 feet deep, covering the continental shelf, and not separated from the open ocean except by the sudden deepening of the water; e.g. off the west coast of Europe, and the North Sea itself (p. 125, Fig. 51).

(*b*) *Epicontinental seas*, 0–600 feet deep (occasionally more), completely land-locked, e.g. Caspian Sea; or more or less separated by islands or peninsulas from the ocean, e.g. Hudson Bay. (pp. 77, 106, Figs. 29, 41).

(2) **Geosynclinal seas**, covering major down-folds of the crust.

(*c*) *Inter-continental seas* (sometimes termed *Mediterraneans*), covering geosynclines between continents; e.g. the ancient *Tethys* (p. 105, Fig. 74).

(*d*) *Liminal* (threshold or border) *seas*, covering continental slopes leading down to the ocean deeps in places where there is no continental shelf, e.g. off the west coast of the Americas; the ancient Devonian and Carboniferous sea of Devon and Cornwall (p. 309).

Life in the Ocean.

It will be appreciated that the hard parts of the organisms living on the sea-floor and in the overlying water [2] contribute largely to the formation of many sediments, especially where terrigenous matter is absent; and that in ancient sediments the organic remains occurring as fossils are of the greatest value to the stratigrapher. For these

[1] T. C. Chamberlin, *Compt. Rend. Congrès géol. Internat.*, XII, 1913, Ottawa, 1914, p. 541. C. Diener, *Grundzüge der Biostratigraphie*, Leipzig, 1925, p. 10.

[2] Near the mouths of large rivers there is an immense amount of decaying organic matter which adds its quota to the food-supply of marine creatures and also directly to marine deposits. The supply of soluble salts in the ocean is also kept up by the rivers. These factors determine the relative poorness of the oceanic pelagic fauna compared with that of the neritic zone, and the general absence of lime-secretion among deep-sea animals and the pelagic plankton.

reasons we must examine the distribution of organisms in the ocean-waters[1] (Fig. 23).

Plant-life, the ultimate source of food for animals, depends on light for its existence. Hence we recognize in the ocean-waters a *Photic* surface-zone, to the bottom of which sunlight is able to penetrate. It is about 600 feet deep where the waters are muddy, but extends to 3,000 feet in clear water in the Tropics. Plants need sunlight, and are therefore limited to it. In the lightless, *Aphotic* waters below, living plants are absent, and herbivorous animals are replaced by mud-eaters and carnivores. Life is far more abundant in the photic zone than elsewhere, especially near the actual surface. This zone may be divided into three regions: *epeiric*, where land-detritus abounds; *hemipelagic*, where this is less important; and *pelagic*, where it is absent as in the open ocean. Roughly speaking, these three regions overlie respectively the areas of the sea-floor where *neritic*, *bathyal* and *abyssal* deposits are accumulating (pp. 49–55).

Marine organisms may be grouped, according to their manner of life, into three main classes: the *Benthos*, the *Nekton* and the *Plankton*.

1. The *Benthos* includes all organisms living on the bottom. Many are *sessile* or attached (e.g. some seaweeds, corals, brachiopods and many other creatures); others are *vagile* or capable of wandering (some molluscs, sea-urchins, star-fish, etc.). The eggs and larvæ of benthonic organisms float in the water and form part of the plankton (see below). This fact accounts for the wide distribution of many fixed or slowly-moving creatures. The Benthos is the most important group in shallow water, but is also found to great depths. It contains the maximum variety of forms, many of which have hard parts. The latter tend to be entombed where the creatures lived. Organic deposits in the neritic zone are usually built up of the hard parts of benthonic organisms.

2. The *Nekton* embraces the swimming animals, like whales, fish and squids.

3. The *Plankton* includes all floating organisms, the majority of which live in the photic zone, e.g. many seaweeds and molluscs, Foraminifera, Pteropods, Radiolaria, etc. The term *Plankton* may be extended to embrace the *Pseudoplankton*, creatures that float attached to planktonic forms (e.g. the extinct Graptolites, p. 267); the *Meroplankton*, organisms that are planktonic for only part of their life (eggs and larvæ); and the *Nekroplankton*, shells of Benthonic forms that float after the death of the creatures (*Nautilus* and some Ammonites, p. 62).

[1] J. Murray, *The Ocean*, chaps. vii and viii. C. Diener, *op. cit.*, pp. 6–8, and for fossil forms, pp. 34–98. R. Hesse, *Tiergeographie*, Jena, 1924, chaps. xii–xv, for relation of marine faunas to their environments.

Dead nektonic and planktonic organisms continually falling through the water from the photic zone all over the ocean, in part contribute to the food of the Benthos, and in part are added to the sediments accumulating on the floor, and in the absence of terrigenous material their hard parts gradually build up organic deposits, especially in the bathyal and abyssal zones as has already been pointed out, e.g. Pteropod, Diatom, Radiolarian, and Foraminiferal oozes (pp. 44, 55). Their skeletons are rarely entombed where the animals lived. Thus a foraminifer living 10 feet below the surface may contribute to an abyssal deposit, 15,000 feet below, and one living in the Tropics may be carried by currents to come to rest inside the temperate zone.

Subdivision of the Ocean Bed (*sensu lato*)

Depth of water, distance from the continents, the type of deposit and the type of organisms, form a basis for dividing the ocean-floor into zones covered by deposits exhibiting different facies (Fig. 23).

1. *Neritic* or shallow-water zone:
   - (*a*) Littoral subzone.
   - (*b*) Shallow-sea subzone.
2. *Bathyal* or deep-water zone.
3. *Abyssal* zone.

The following is a synopsis of the characteristics of the life and environment of the present-day sea-floor in the different zones, and of the corresponding deposits,[1] some of which are briefly discussed. Ancient deposits of similar types are also referred to.

1. Neritic Zone.—From 0 to –600 feet; mainly in epeiric seas.

Water agitated to the bottom by waves and currents.

Daylight penetrates to the bottom (see p. 48).

The mean surface-temperature varies with geographical position from 80° F. (Sunda Sea) to 27° F. in the Antarctic.

Marked seasonal variations of temperature.

Often much terrigenous and carbonaceous material in suspension.

Great variety of bottom, water-temperature, and salinity; and corresponding variety of Benthos.

Abundant plant-life.

Animals both herbivorous and carnivorous; Benthos often sessile and adapted to resist currents and wave-action, and in the littoral subzone the ebb and flow of the tides also, and the consequent exposure to the air.

(*a*) *Littoral Subzone.*—From 0 to –60 feet; the beach and fore-

[1] See espec. E. Haug, *Traité de Géol.*, vol. i, chap. v. H. R. Mill, *Realm of Nature*, 2nd ed., chap. xii. Sir John Murray, *The Ocean*, chaps. vii–ix. J. Johnstone, *Oceanography*, chap. iv. R. Hesse, *Tiergeographie*, chaps. xii–xv.

shore, and immediate vicinity of the coast, including estuaries and coastal lagoons (p. 325), and coral-reefs (p. 100).

Typical deposits are boulders, shingle and gravel, sands, shell-sands, coral-sands and -muds, and black muds full of vegetable matter; algal,[1] coral- and bryozoan-limestone.

Beach-gravel, sand and mud may occur on the same shore as one goes seawards, but traced along the coast their distribution seems to depend on accidents of tides, waves and wind. In some places the currents and waves keep the bottom swept clean, and no sediment is deposited (p. 133).

In coastal deltas, swamps and lagoons, either gravels, sands or carbonaceous muds may be laid down. Often the aspect of these environments changes greatly with the season and with the shifting of river courses; sedimentation may be succeeded by erosion or one type of deposit by another. Estuarine and deltaic deposits are often heavily charged with the debris of plants, and may also entomb side by side the remains of terrestrial, fluviatile, and marine organisms. In a rock-series of estuarine origin the fossils frequently reveal alternations of fresh- and salt-water deposits. This results, as a rule, from slight alterations of sea-level (p. 323); but this is not the only possible cause, for in some estuaries there are layers of water of different salinity, so that at one and the same spot freshwater organisms may occur at the surface, and brackish or even marine types at greater depths.[2]

A very different type of littoral environment is found where the water is free from mineral and vegetable detritus, as, for instance, round oceanic islands or on sea-boards where rivers are few. In arctic and temperate regions the shingle and boulders of the beaches contain comparatively few remains of organisms; but in the Tropics organic reef-deposits are a conspicuous feature of many such coast-lines. The best-known reefs are the coral-reefs of the western sides of the Pacific and Atlantic, and of many parts of the Indian Ocean and Red Sea. Some reefs are formed mainly by corals, but others are due to Bryozoan and Lithothamnium growths. A reef is not, however, built up exclusively of the hard parts of such fixed benthonic organisms, but includes the shells of molluscs, sea-urchins, crabs, foraminifera, etc., reinforced by ooliths, coral-sand and coral-mud, by the secretion of algæ, and even by calcareous precipitates.[3]

[1] D. Mawson, "Some South Australian Algal Limestones in Process of Formation," *Proc. Geol. Soc.*, 1929, No. 1197, p. 70.

[2] C. Diener, *Grundzüge der Biostratigraphie*, 1925, p. 16. H. Munro Fox records a similar phenomenon in the salt Lake Timsah on the Suez Canal. *Trans. Zool. Soc.*, vol. xxii, 1929, p. 844.

[3] For a full discussion of modern coral-reefs in the light of recent work, see W. M. Davis, "The Coral Reef Problem," *Amer. Geogr. Soc.*, Spec. Publ. No. 9,

The distribution of reef-building corals is governed by three principal factors:

1. Uniformly warm waters, the average temperature of which does not fall below 71·6° F. (22° C.);
2. A depth not exceeding 20–25 fathoms;
3. Clear waters, free from mud in suspension, and of not less than normal salinity.

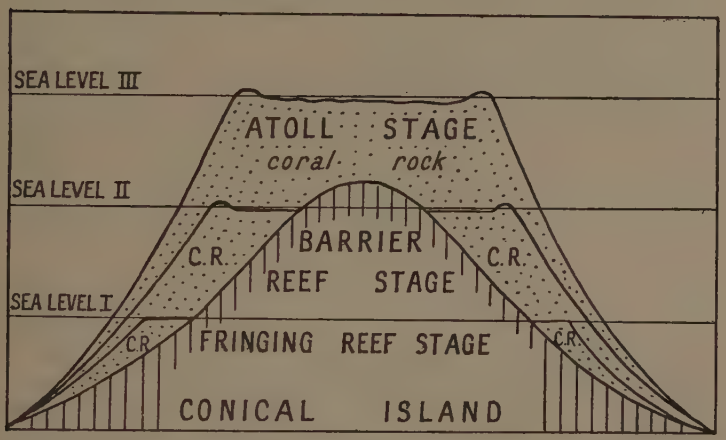


FIG. 25.—The three stages of coral-reef development on Darwin's hypothesis.

The formation of coral-reefs and coral islands is best explained as follows. Under favourable circumstances the accumulation of coral and other organic growths forms a *fringing-reef* around islands or along the coast of continents.[1] Coral growth is always greatest on the seaward side, and in this way the reef extends outwards and may acquire a lagoon between itself and the land. Such an arrangement is termed a *barrier-reef*. Darwin's theory of the formation of coral islands and atolls demands, however, a gradual sinking of the crust that is compensated for by upward growth (Fig. 25). In this way an island with a fringing-reef becomes an island with a barrier-reef, and this in turn becomes an *atoll*, i.e. a ring of coral islets and reefs, with a central lagoon in place of the central island. A boring on the atoll of Funafuti, by proving coral-material to a depth of 1,114 feet, confirms this

1928. R. Hesse, *op. cit.*, pp. 216–231. Also J. Johnstone, *op. cit.*, pp. 79–88; A. W. Grabau, *P. of S.*, pp. 385–416.

[1] Fossil-reefs recognized in the strata of past ages were evidently formed in relatively shallow seas and may have originated by coral and other organic growths on shoals (M. O. Ogilvie Gordon, *Geol. Wandesbuch d. westlichen Dolomiten*, 1928, pp. 25–28), for any relationship to coast-line can rarely be proved (p. 316); see, however, p. 100.

view. Many oceanic coral islands and atolls rise to the surface from great depths and are probably founded on volcanoes.

A sinking continental coast, on the other hand, would according to the theory be bordered by a barrier-reef. A recent boring on the Great Barrier Reef of Queensland proved 427 feet of coral-material, and affords further support to the theory. W. M. Davis's reinvestigation of the coral-reef problem entirely substantiates Darwin's theory and shows the inadequacy of all others. His book, however, should be referred to for a full discussion of the rival theories.

Present-day "coral limestones" forming in regions remote from land are characterized by their great freedom from detrital matter, other than an occasional admixture of volcanic dust.[1] A more or less contemporaneous change of the calcareous matter to dolomite may take place, as shown by the exploration of the "atoll" of Funafuti.[2] This may be accompanied by the loss of many of the original structures.

Amongst ancient deposits, conglomerates, irregular sandstones, carbonaceous shales, clay-ironstones, calcite-mudstones, some reef-limestones and oolitic limestones are the more important littoral types. Occasionally a wave-cut surface bored by molluscs or worms may be the sole evidence of a former littoral zone. All littoral deposits are peculiarly susceptible to the effects of slight changes in sea-level, and to small alterations in the conditions that govern deposition along a coast. Hence each tends to be local and to have a lenticular rather than a sheet-like form. A rock-series built up of such deposits varies rapidly both in vertical sequence and from place to place. In it there is frequently evidence of contemporaneous erosion and of non-deposition, so that it does not present a complete record of the period covered by its formation (pp. 133, 144).

As regards the contained fossils, since the types of animals occupying the coastal belt vary greatly with the different habitats, and since we may be sure the same was the case in the past, it is natural to find in ancient littoral deposits a *diversity of contemporaneous faunas* (see p. 61).

(*b*) *Shallow-sea Subzone.*—From the littoral subzone to –600 feet. Typical deposits are sands, shell-sands, nullipore and polyzoan sands, greensands, volcanic and coral-sands, some ironstones, muds, carbonaceous muds, and occasionally shingle, gravel, and deposits of oyster shells, etc.

Compared with the littoral, there is in the shallow-sea subzone a greater uniformity of environment and consequently a greater uniformity in the type of sediment. In many seas, sand is the most

[1] E. W. Skeats, *Q.J.G.S.*, vol. lxi, 1905, p. 100.

[2] *The Atoll of Funafuti*, published by Roy. Soc., Lond., 1904.

usual deposit; but where there are large rivers, blue mud and occasionally red mud may be widely distributed. The sands are composed partly of terrigenous detritus and partly of fragments of shells. There are also true shell-sands and limestones made up of the hard parts of molluscs, sea-urchins, nullipores, polyzoans, etc., whole or broken, Coral-sand occurs in the tropics in the neighbourhood of coral-reefs. and volcanic sand around active vents. Glauconitic "greensand" is another unusual variety.[1]

Amongst *ancient shallow-sea deposits*, the usual types are sandstones, shelly sandstones, greensands, ironstones, silts, shales and clays, calcareous clay, limestones rich in fragments of the hard parts of molluscs, sea-urchins, crinoids, nullipores, bryozoa, etc. Such deposits may be expected to form fairly wide sheets of contemporaneous material, but owing to the power of tidal currents [2] in this subzone they are liable to rapid changes of thickness or to sudden terminations.[3] Nevertheless, the zone in which they were laid down offers a far more uniform habitat than does the littoral zone. At the present day the faunas are less diversified and cover greater areas than in the latter; but are nevertheless restricted, each to its own particular environment, by physical factors, such as temperature, salinity, etc.[4] The fossil faunas, in that they lived under similar conditions, show a puzzling variety of contemporaneous species, but usually contain a sufficient number of forms in common to enable us to correlate contemporary shallow-sea deposits over fairly wide areas (p. 61).

2. Bathyal Zone.—From –600 to –3,000 feet; mainly in geosynclinal seas.

Bottom formed by terrigenous muds or organic oozes, and gently swept by ocean-currents.

Very little light. Temperature nearly constant at any one place.

Living plants deficient or absent.

The benthonic animals are mud-eaters or carnivores.

Species have wider geographical distributions than in the neritic zone.

Typical deposits are: blue, red and green muds,[5] coral-muds, calcareous muds, and occasionally organic oozes.

Bathyal environments vary more gradually and within narrower

[1] L. W. Collett, *Les Depots Marins*, 1908, pp. 155–7, 188. W. H. Twenhofen, *op. cit.*, pp. 337–341. J. Murray and A. F. Renard, *Deep Sea Deposits*, *Challenger Reports*, 1891, pp. 240, 389.

[2] They are also liable to be elevated into land, and to be eroded.

[3] For a consideration of the effects of rising or falling sea-level on the distribution of a particular lithological type in time and space, see p. 141.

[4] C. G. J. Paterson, *Rep. of the Danish Biological Station*, 1913, discussed by G. L. Elles, *Rep. Brit. Assoc.*, 1923, p. 84. Also R. Hesse, *op. cit.*, chap. xii.

[5] Coloured respectively by iron pyrites, ferric oxide, and glauconite.

limits than the neritic. In them the finest detrital material carried thither by currents or blown in by the wind come to rest as mud. "Blue mud" covers the largest areas. Away from land, however, owing to the accumulation of planktonic debris and the absence of terrigenous detritus, calcareous muds, and even organic oozes, may be the principal deposits (p. 164).

In some bathyal stations, e.g. the deeper parts of the Black Sea, where owing to peculiar conditions of circulation oxygenated water does not reach the bottom, black sulphurous mud is found, and there is very little benthonic life except anaerobic bacteria (p. 269), some of which are capable of reducing sulphates to sulphuretted hydrogen, and thus produce deadly bottom-conditions.

Ancient bathyal deposits show uniformity in lithology and fossil-contents over very wide areas (e.g. the black graptolitic shales of the Ordovician, the shales of the Lias, the Chalk, and the "Nummulite Limestone" of the Eocene). Correlation of contemporary strata over areas of international dimensions by means of the contained organisms is also comparatively easy and reliable.

Neritic and Bathyal Deposits contrasted.—The neritic zone has not, as a rule, been favourable for the formation of great thicknesses of rock. The deposits show rapid changes of lithology and fossils (i.e. of facies),[1] both vertically and horizontally. They present an incomplete record of the time covered by their formation; for deposition has frequently been interrupted by submarine or sub-aerial erosion. The breaks produced are non-sequences and unconformities (pp. 63–66) that record contemporaneous movements, often only slight, yet capable in shallow-water and coastal environments of producing profound changes. Sometimes neritic rocks contain fossils that give glimpses of the life on adjoining lands, and not infrequently actual continental deposits are intercalated.

On the other hand bathyal sediments have accumulated in the past in geosynclinal seas to colossal thicknesses. They are characterized by slow and gradual changes of lithology and fauna, both in vertical succession and from place to place; by continuity of sedimentation and of fossil lineages (p. 166); and by the absence of littoral and continental intercalations.

Haug points out [2] that neritic and bathyal sediments often undergo very different fates. The former being comparatively thin, and usually deposited over some part of an already consolidated continental block, have rarely been much folded or changed; whereas the accumulation of vast thicknesses of bathyal deposits has ever been the prelude

[1] Facies is the sum of the lithological and palæontological characters, and indicates the environment under which the rock was formed (see pp. 61, 145).

[2] E. Haug, *Traité*, vol. i, p. 158.

to an energetic mountain-building that has dislocated and metamorphosed them (e.g. the Alpine mountain-chain on the site of the Mesozoic geosyncline of Tethys (see pp. 170–5), and the Caledonian chain on the site of the Lower Palæozoic geosyncline (Fig. 111).

3. Abyssal Zone.—From –3,000 feet to the greatest depths (–32,300 feet).

Daylight absent.

Bottom absolutely quiet, with a temperature nearly constant throughout the world (35° to 29° F.), except in land-locked seas separated from the open ocean by elevated sills (e.g. Red Sea).

Plants absent, and benthonic animals scarce. Deep-sea nekton with special adaptations to high pressure and want of light.

Dead plankton falls to the ocean-floor (p. 44).

Typical deposits are organic oozes in the shallower, and "Red Clay" in the deeper parts (p. 44). The latter covers a quarter of the whole surface of the globe.

Ancient abyssal deposits are rarely found as rocks at the surface. The Chalk and various other deposits have with doubtful correctness been claimed as such (see p. 164). The best substantiated occurrence is the Radiolarian *Barbados Earth* [1] and associated red clay and calcareous earths, which contain fossil and other evidence of an origin at depths varying from 6,000 to possibly 18,000 feet.

Changes during Consolidation (Diagenesis).

Most rocks as first deposited contain a great quantity of water. During consolidation they are compacted by the pressure of the overlying newer formations, and the total thickness is decreased. The diminution, greatest in peats [2] and muds, is less in sands, and possibly negligible in conglomerates and limestones. This differential contraction sometimes produces appearances that simulate the effects of earth-movement (p. 110). So too do the landslip-like disturbances that may occur on steep submarine slopes (p. 339) (deltas and "Pacific slopes").

In addition to these mechanical changes, chemical reactions lead to alterations in the mineral composition (metasomatism, coal, etc.) and to the precipitation of new substances as cementing material between the particles forming the sediment. Recrystallization may also occur. A consolidated rock usually therefore differs widely from the sediment as first laid down.

[1] A. J. Jukes-Browne and J. B. Harrison, "Geol. of Barbados," II, *Q.J.G.S.*, xlviii, 1892, pp. 170–225.

[2] This is here due to loss of volatile hydro-carbons and carbon dioxide, as well as of water.

II. THE PRINCIPLES OF STRATIGRAPHY OR HISTORICAL GEOLOGY

CHAPTER V

THE NATURE OF THE GEOLOGICAL RECORD

Aims and Material.—Stratigraphy aims at unravelling the history of the earth, and is for this reason sometimes termed Historical Geology. The distribution of land and sea, mountains and plains, rivers and lakes, the climate and life, earth-movements and vulcanicity of each epoch make up its geography; and it is the duty of the stratigrapher to deduce these features for each epoch from the record of the rocks. Not only so, but he has to reconstruct the whole sequence of past geographies [1] that have succeeded one another from the earliest days to the present; and to show how the present geography has been evolved by a continuous series of changes that stretch back past the dawn of life to the birth of the world.

The following table shows the type of data from which the geographical environment of a place at a particular epoch is deduced:

TABLE I

Nature of the Data.	Deduction.
Presence or absence of marine, continental, coastal or estuarine deposits	Distribution of land and sea.
Unconformities (pp. 64–66)	Ditto.
Type of unconformity	Nature of land.
Facies of continental deposits, e.g. lacustrine, deltaic, salt-lake, volcanic, etc.	Ditto.
Facies of marine deposits	Nature of the sea.
Unconformities and non-sequences	Earth-movements and erosion.
Variation in thickness of sediments	Ditto, ditto.
Diastrophism (folding, faulting, etc.)	Ditto.
Metamorphism	Ditto.
Extrusive and intrusive igneous rocks	Vulcanicity.
Metamorphism	Ditto.
Fossils and nature of deposits, e.g. glacial, arid, etc.	Life and climate.

In previous chapters many of these phenomena have been dealt with, especially those relating to facies and earth-movement. Un-

[1] W. W. Watts, Presidential Address to Geol. Soc., *Proc. Geol. Soc.*, vol. lxvii, 1911, p. xcii.

conformities, non-sequences and the use of fossils will be discussed shortly; but it is necessary first to show how it is possible to recognize and correlate from place to place the rocks belonging to any particular epoch; for before any deductions as to the geography can be made, we must satisfy ourselves that the geological data from which we are inferring them are all products of a single epoch, and that we can place that epoch in its correct chronological relation to those that preceded and followed it. This identification and correlation is effected by a study of the order in which the strata occur, their extent, their lithological and palæontological characters, and their associated igneous rocks.

Order of Superposition.—In the first place it is necessary to establish the vertical order in which the strata and extrusive volcanic rocks were originally arranged. This is termed the order of superposition, and is found by direct observation of natural and other exposures. Once discovered, it gives for a particular area a key to the relative ages of the rocks, the older below, the newer above. The order observed, however, is not always the true one, for highly disturbed rocks are often inverted in overfolds, and faulting also may carry older rocks on to the top of newer ones (Figs. 2 B and 116, p. 277). Nor does the order of superposition hold in the case of a stratiform *intrusive* rock which, though it appears to be interbedded, may belong to any period subsequent to the formation of the newest rock into which it has been introduced. Such an intrusion must be carefully distinguished from a contemporaneous flow of lava that is truly interbedded between rocks that are respectively older and newer than itself, and thus occupies its real stratigraphical position in the sequence. It will be seen in the sequel (pp. 63–66) that the superposition of one bed on another is no proof that they were the products of two directly successive periods; but this does not nullify the principle of superposition.

Correlation of Strata.

(*a*) *Direct.*—The correlation of sequences established in adjacent districts can sometimes be effected by following one or more of the formations from one area to another. Owing to the possibility of lateral change in the facies (p. 321) this method has to be applied with due precaution; but under favourable circumstances fairly accurate correlations can often be established in this way. But where the districts are widely separated geographically, or where the facies of the rocks is changing rapidly, this method breaks down.

(*b*) *By Lithological Character.*—The chemical and mineral composition of the rock, the abundance, scarcity or absence of certain minerals, the nature and derivation of the fragments contained as

pebbles in it, the state of weathering, the amount of metamorphism and metasomatism to which it has been subjected, and its mutual relations to other formations in the district, are all features that have to be taken into account in correlating it by lithology with strata occurring elsewhere, that are regarded as possibly contemporary.

(*c*) *By Fossils.*—Even when the above methods have been applied, they are always supplemented, if possible, by a system of correlation based on the use of fossils. The term *fossil* is given to the remains or traces [1] of organisms preserved in the rocks. Generally they are the hard parts, or more usually replacements (pseudomorphs), impressions, or casts of the hard parts, of plants or animals that were alive at the time when the rock was in process of formation. As the organisms died, their remains were incorporated in the rock, and are therefore termed contemporary fossils.[2] They show us a glimpse of the life of the period.

William Smith (1769–1839), a civil engineer, working at the beginning of the nineteenth century, was the first to realize the stratigraphical value of fossils as indicators of the relative ages of the rocks that contained them. In his examination of the little-disturbed rocks of the Midlands and Yorkshire he found that he could not only trace the different beds from one district to another by their lithological or rock-features, but that the several formations were characterized each by its own particular suite of contained organisms. His book *Strata identified by Organized Fossils*, 1816, while earning for him the nickname of "Strata Smith" and the title of "Father of English Geology," marked the beginning of a new era in stratigraphy.

The value of William Smith's work lay in the fact that he was the first to prove by direct observation that certain fossils were confined to certain strata. Realizing that fossils are remains of creatures contemporary with their containing rock, and being able to show by mapping that these containing rocks could be arranged in a regular and constant order of superposition or, in other words, in the order of their relative ages, he proved that the fossils could also be arranged in the same order. His deduction is a prime principle of stratigraphy.

[1] Occasionally fossils are merely traces of organisms, e.g. fossil footprints, p. 85, and flint implements, p. 245.

[2] The term "contemporary" is applied to distinguish them from "derived" fossils, which are fossils that have either been washed from their natural containing-rock and incorporated in the same way as pebbles in a newer formation, or fossils that occur in pebbles contained in a newer formation. In the absence of contemporary fossils, derived ones are of use; for they show that the formation in which they occur is of a later date than the period to which the fossils originally belonged. This knowledge may be of use in dating otherwise unfossiliferous conglomerates. On the other hand, the non-recognition of the derived nature of fossils has more than once led to erroneous conclusion.

It is that the geological age of a rock can be fixed, irrespective of its lithology or relations to other formations, by finding in it fossils, the geological ranges of which have already been determined elsewhere by applying the principle of the order of superposition.

Smith's work was mainly on the Mesozoic rocks of England. Innumerable workers have since been occupied in extending his work to other suites of rocks, and in filling in the details. The sequence of rocks and their fossil-contents in district after district has been, and is being, thus gradually elucidated. Our knowledge of fossil-organisms and of their orderly sequence in time is now so great that it is possible to go to regions geologically unknown and widely separated from well-known sequences, and yet be able to identify the approximate geological ages of the rocks met with, solely by means of their fossil-contents.

Though the limitation of particular fossils to rocks of a certain geological age was originally determined empirically, and though the earlier workers used this information empirically, the principle has stood on a far wider basis since the general acceptance of the idea of organic evolution. The whole conception of evolution postulates that the nature and fashion of the organisms has been changing as the long ages rolled by, never to recur again in exactly the same guise. It follows, therefore, that the recurrence of identical creatures at widely separated periods of time is on the evolutionary hypothesis impossible. Moreover the correctness of the hypothesis has been repeatedly confirmed by the discovery that hardly any species, if really critically examined, can be shown to have persisted for a long time without undergoing some changes in shape or organization. So long as we cannot discover intermediate forms, fossils that are evidently closely related, yet found at different horizons, must necessarily be regarded as independent species; but as the intermediate stages become known, it is sometimes possible to see that species which at first appeared distinct, are in reality only rungs on the evolutionary ladder. A series of such *mutations*[1] (i.e. varieties that appear in a stock as time proceeds), in that they mark stages in the irreversible evolution of that stock, are especially valuable as time-indicators[2] (Fig. 26).

The use of fossils for purposes of exact time-correlation is not

[1] This term has unfortunately been applied by some biologists to suddenly-appearing conspicuous varieties of plants or animals. The usage of the term as here explained has, however, priority.

[2] See discussion on the evolution of *Micraster* in the Chalk (p. 166), and A W. Rowe, *Q.J.G.S.*, vol. lv, 1899, pp. 494–546. Also R. G. Carruthers, "Evolution of Zaphrentis delanoui," *Q.J.G.S.*, vol. lxvi, 1910, p. 523. W. D. Lang, "Trends in British Carboniferous Corals," *P.G.A.*, vol. xxxiv, 1923, p. 120. H. H. Swinnerton, *Outlines of Palæontology*, 1923, pp. 55–8. E. Neaverson, *Stratigraphical Palæontology*, chap. vi, with references.

without its difficulties, and has to be subjected to rigorous precautions. In the first place all fossils are not of equal service for this purpose. The rate at which the organisms, or even their individual organs, evolved, is of prime importance. Fossils with short time-ranges are essential for exact-correlations; for slowly-varying forms are of little

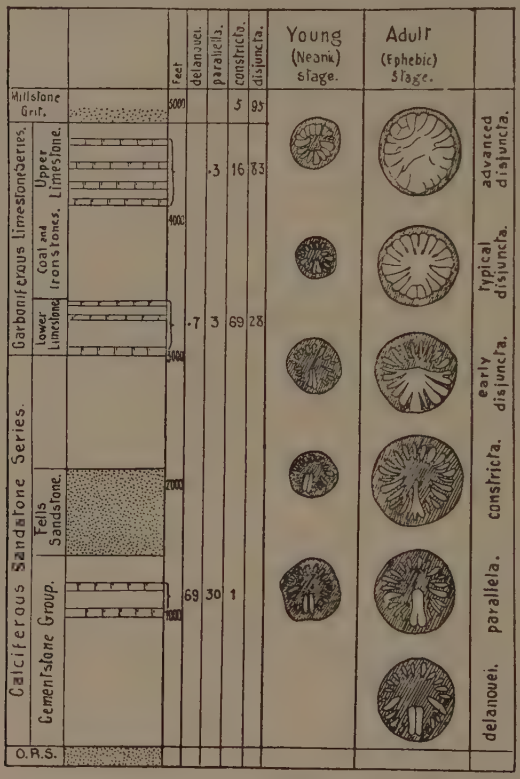


FIG. 26.—Mutations within the gens, *Zaphrentis delanoui*.

Diagram to show the changes in structure of the skeleton, distribution of the mutations in time, and their relative abundance at four dates. After H. H. Swinnerton.

value (though useful in pioneer work), because they are found throughout too great thicknesses of strata. As has just been pointed out, the range of a form may often be found to be shorter than supposed, if its anatomy be subjected to a really critical examination. Even so there appear to have been creatures that the Germans call "unsterblich" (immortal), that have remained practically unaltered through countless ages.

Secondly, forms having a wide geographical range, e.g. the open-sea floating creatures (i.e. the *pelagic* and *hemipelagic plankton*), and the inhabitants of the widespread mud zones (i.e. the *bathyal benthos*,[1] p. 53), are obviously more suitable for correlation purposes than those neritic and continental organisms that have a restricted distribution by reason of their adaptation to specialized environments, the nature of which is often determined by quite local conditions. The exacting control of terrestrial environments over plants and animals has long been recognized, and recent zoological research has shown that marine animal-communities also are extraordinarily restricted by depth, temperature, bottom, light, salinity, currents, food-supply, etc.[2]

Apart from this restriction to particular habitats, there were in the past, as there are to-day, zoological provinces or regions characterized by certain distinctive plants and animals, so that neighbouring similar habitats may not necessarily have supported the same flora and fauna, and it is possible to have in beds of the same age and formed under similar conditions of depth and bottom, faunas that differ greatly owing to their having belonged to different provinces. The contemporaneous marine faunas of the Red Sea and Mediterranean on either side of the Isthmus of Suez afford a present-day example. Also in a continuous series of similar strata some of the changes in the fauna may be due to the migration of creatures from their usual province into a neighbouring one. This has, for example, been observed among the trilobites of the Welsh Ordovician.[3]

It should now be clear that each habitat in the past possessed at any particular time a peculiar assemblage of organisms which, so far as they are preserved as fossils, provide a particular faunal assemblage in the rock that contains them. Where the habitat was a widespread one (e.g. the bathyal zone), there the fossils can be readily used for correlating over extensive areas; but where the habitat was a restricted one, there the fossils are less useful for correlation, but tell us much about the nature of the habitat. They are then often termed *facies-fossils*. If such fossils have evolved slowly, we must avoid the mistake of regarding a similarity of facies-fossils as proof of equality of age[4] (p. 163).

Experience alone can tell whether a particular fossil has a sufficiently restricted range in time and a sufficiently extended geographical

[1] Some neritic forms with floating larvæ are also widely distributed.

[2] C. H. J. Patersen, *Rep. Danish Biol. Station*, 1913. R. Hesse, *op. cit.*, chap. xii, especially pp. 199–203.

[3] G. L. Elles, *Rep. Brit. Assoc.*, 1913, p. 490. For a study of present-day migration, see H. Munro Fox's report on migration in the Suez Canal. *Trans. Zool. Soc.*, vol. xxii, 1926, p. 1, and 1929, p. 843.

[4] W. B. R. King, *Q.J.G.S.*, vol. lxxxiv, pp. 677–679, discusses a good example.

distribution, to allow it to be useful for detailed correlation of strata over wide areas. Every fossil is, however, useful as a member of a fauna, and it is really the faunal assemblage that should be used as far as possible for correlation purposes.

The term *homotaxial* is applied to rocks containing similar faunas and therefore, geologically speaking, contemporaneous. Yet if the rocks occur in widely-separated localities, the formation of the one may have been later than that of the other by the length of time required for the fauna to migrate between the two places. It is likely, however, that in general this length of time compared with that involved in the evolution of the next succeeding fauna, is short enough to be neglected, except in the most detailed work. The different ranges of time covered by certain Ammonites in the Alpine and Mid-European developments of the Mesozoic rocks may be partly explained in this way.

The smallest thickness of strata that can be distinguished by the possession of a characteristic fauna or flora is known as a *Zone*. The same zone may vary in thickness from place to place from a few inches to hundreds of feet. The accuracy with which a zone can be defined and recognized varies also with the number and preservation of suitable fossils, the assemblage of fossils being more important than the presence of one or two particular species, for the time range of any one species may vary from district to district owing to migrations and to differences of environment. For convenience' sake, however, each zone is named after a particular fossil.

A *moment* or *zone-moment* is the period of time occupied in the formation of a zone, and can therefore only be defined by the use of fossils. While a zone-moment is the unit division of geological time, the actual length of time covered by different "moments" varies with our ability to define the zones, being shorter in proportion to the abundance of suitable fossils, and inversely proportional to our ignorance about them. The nearest approach to the ideal yet attained is in the subdivision of Jurassic time. Here the abundance, variety, and wide distribution of the Ammonites permits us to define the limits of each zone with great precision. The most detailed Ammonite-zoning in this country is that effected by Buckman, who has divided the rocks up into very minute zones each held to be characterized by the abundance of one species. Since these zones are subdivisions of broader zones that were established long ago, they are commonly referred to as sub-zones.[1] He has instituted the term *hemera* to denote the short time occupied in the formation of such a sub-zone, and has defined it as the period during which a particular

[1] A. E. Trueman has suggested the term *epibole* for the deposits formed during a hemera. *P.G.A.*, vol. xxxiv, 1923, p. 200.

species attains its acme of development (p. 138). Usually it is impossible to divide the strata into zones that correspond to hemeræ in this latter sense. In most systems a zone embraces the strata deposited during a much greater length of time, and the period it covers more commonly represents the acme of development not of a species, but of a genus, or even of a family.[1]

In certain cases apparently unbroken sequences of similar sediment have been found. Usually they are of the bathyal type, and possess a fairly wide distribution in space and a similar type of fauna whenever they are met with. Such, for example, are the black Graptolite-bearing mudstones of the Ordovician, and the dark shales with Ammonites and Belemnites in the Jurassic just referred to. Such rocks, it has been shown above, are susceptible to accurate zoning, and on account of the completeness of the geological record preserved, the zones established in them become a sort of standard-sequence or reference time-scale that is found to hold good over a large region, and sometimes to have an almost world-wide distribution.

Where such a standard-sequence of zones has been established for part of the geological record, it is usual to correlate with it, as far as possible, the other contemporary facies. This is effected in various ways. Thus intercalcations of strata containing the standard-facies may occur among the rocks of the second facies, or there may be an intermixture of the faunas. The use of intercalations is especially valuable in correlating continental facies with marine ones. Instances of the correlation of diverse contemporary facies are given in the sequel (pp. 145, 185 and Fig. 112).

Gaps in the Geological Record.

(1) **Diastems.**—Even where a rock-series exhibits no visible break, it is not permissible to regard it as a record of continuous deposition, for such is a rare phenomenon. Generally only a fraction of the time embraced in its formation is represented by rock. The planes between successive conformable beds may correspond in the aggregate to a far greater length of time than that occupied in the deposition of the beds themselves. Such gaps are called *diastems*.[2]

(2) **Non-sequences.**—If a succession of zones has been established on a satisfactory basis in one district, the absence of one or more zones from an apparently unbroken conformable sequence in another area is usually regarded as proof that those zones were either never

[1] For a discussion of principles of zoning, etc., see C. Diener, *Grundzüge der Biostratigraphie*, 1925, Section 8. G. L. Elles, *Rep. Brit. Assoc.*, 1923, p. 87. E. Neaverson, *Stratigraphical Palæontology*, 1928, chaps. i, iv, and v. A. E. Trueman, *op. cit.*, 1923, with many references.

[2] J. Barrell, *Bull. Geol. Soc. America*, vol. xxviii, 1917, p. 794.

deposited there or, if deposited, were eroded away by current-action. Such a gap in the succession of palæontological zones is termed a *non-sequence*. It is sometimes indicated by signs of erosion that have often remained undetected until the faunal break has been discovered. Some non-sequences pass laterally into unconformities (see below) and in this case indicate contemporary uplift of the sea-floor, which brought the sediments there accumulating within the reach of current-erosion without, as in the case of an unconformity, elevating them into land (p. 144). In other cases there is no proof of uplift, and the non-sequence is best explained by assuming either a change in the direction or strength of currents or pauses in the general subsidence of the sea-floor.

(3) **Unconformities.**—It has been pointed out that erosion is initiated as soon as rocks are elevated to or above sea-level, and that through erosion the new land-surface is carved into hills, valleys, and wave-cut platforms, and, if time enough be given, is gradually reduced to a peneplain almost at sea-level (p. 36). But the movements are not consistently upwards; a reversal may take place, and the land-surface be submerged. Under these circumstances, new sediments (often littoral in origin) may be laid down horizontally across the worn-down edges of the older series. The arrangement constitutes a true *unconformity*; so called because there is in many parts of its extent a want of conformity in the dip and strike in the newer and older series.[1] Sometimes an unconformity is detected by a change from metamorphic to unmetamorphosed rocks, or from highly to slightly metamorphosed ones. This method of detection is of particular importance in the Pre-Cambrian systems. An arrangement of rock formations mimicking an unconformity is sometimes due to thrust-faulting (pp. 279–80).

An unconformity indicates a lapse of time during which either no deposition took place in the area or, if sediments were formed, they were subsequently denuded. Some unconformities represent enormous periods, and are then usually found to occur over large regions; others of more local distribution can be shown to represent the omission of only one or two zones. The greater the lapse of time, the more marked will be the break in the faunal sequence at the surface of unconformity. A striking difference in the faunas

[1] There are, however, frequently places where the bedding in the two series happens to be parallel or nearly so (e.g. at X in Figs. 38 and 47), the unconformity being revealed by the fossils or perhaps by some characteristic lithological feature. If the gap thus shown is a considerable one the arrangement implies an unconformity and not a non-sequence (p. 63), e.g. near Elgin fossils show that Permian Sandstones lie apparently conformably on Old Red Sandstones. This gap involves a time-interval equal to at least the whole Carboniferous period, and must therefore be regarded as an unconformity.

may, however, be deceptive; for at an unconformity the overlying series has commonly been deposited under an environment quite different from that obtaining at the time when the older series were being formed, and under these circumstances even if the two series were nearly contemporaneous many of the fossils would be different.

Unconformities are of two types:

1. *Transgressions*,
2. *Buried landscapes*,

which, however, merge into one another, and into *non-sequences*.

(*a*) *Type* 1. Figs. 38, 115. When a nearly horizontal surface has been produced either by subaerial denudation or by marine erosion, a comparatively small depression of the land allows the sea to advance over wide areas. Unconformities of this type affect large regions (p. 163) and are known as *transgressions* (Fig. 38). In them there is marked *overstep*, i.e. the lowest member of the newer series rests successively on different subdivisions of the older. *Overlap* or the horizontal extension of the higher members of the upper series beyond the limits of the lower members of that same series, is less rapid than in the second type now to be considered.

(*b*) In *Type* 2 (Figs. 47, 115, 129) it is a hilly, uneven landscape which has either been submerged below the waters of the sea or of a lake, or has been buried under the debris of its own screes or by glacial deposits. Owing to ancient surface-inequalities, the upper members of the new series may overlap the lower members rapidly, and each member of the newer series is thus lenticular in shape. The lowest member of the newer series varies in age from place to place (pp. 108, 254, Fig. 47).

Unconformities are invaluable in our attempts to reconstruct past geographies, for they help us to define coast-lines, and the shape and nature of the land-masses; and to picture the erosion that was in progress immediately before the newer series of strata was deposited. The amount and nature of the distortion that the older series had previously undergone can be judged from a comparison of its structure with that of the newer rocks. This should show us whether the movements that elevated the older group were epeirogenic or orogenic, and thus throw light on the position of ancient mountain-chains and stable blocks of the crust. The time involved in the unconformity can be dated as between the youngest formations present in the older series and the oldest one found in the newer; and thus we are often enabled to determine within certain limits the geological date of the earth-movements involved.

Minor unconformities come into being along the margins of the land-areas and are due to oscillations of the relative level of land and sea, accompanied sometimes by orogenic movements (e.g. those along

the edge of the lower Palæozoic geosynclinal sea, p. 271). They often have a quite local distribution. Major unconformities, on the other hand, may be found over areas of continental dimensions, and in some cases over even vaster regions. Each records the progress of the large crustal movements by which a new continent came into being and by which the relation of land and water was disturbed, possibly over the whole globe. The movements were not simultaneous all over the area involved, nor were the land-surfaces thus brought under the influence of denudation, buried uniformly under new sediments

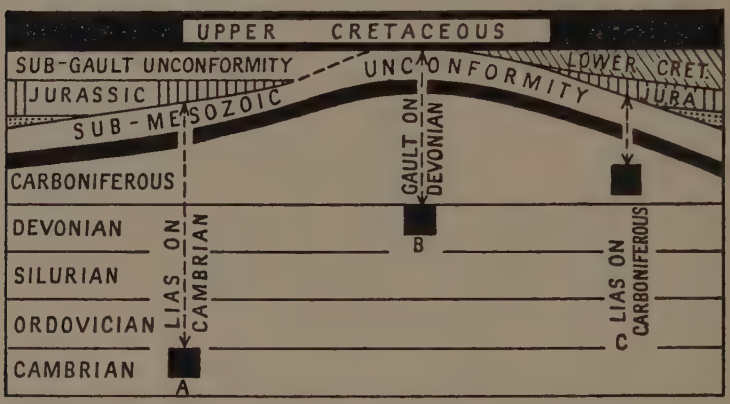


FIG. 27.—Diagram of the sub-Mesozoic Unconformity in S.E. England, showing the Time-value of the Unconformity at three points, and that the gap begins and ends at different horizons.

A, Bletchley; B, London; C, Kent; T, Trias.

In one place the new deposits were continental, in another marine: one part was quickly buried and another remained dry land for ages. We may cite as examples the unconformity that separates the Mesozoic from the Palæozoic in most parts of Europe. Fig. 27 shows the time-value of this unconformity at places in South-East England and also indicates how the sub-Gault unconformity merges with the sub-Mesozoic in the neighbourhood of London. Such widespread transgressions may have secular causes (see p. 8), such as changes in the shape of the earth or in the position of the poles.

Subdivision of the Geological Record.

From what has been said above, it is clear that a sequence of rocks can usually be subdivided into zones by means of fossils. It can also be divided according to lithological facies—shales separated from limestone, etc. The lithological nature may locally serve to identify a rock; but when traced laterally, the lithology may change or, if it

persists unaltered, the contained fossils not infrequently show that the lithological unit does not correspond with a constant period of geological time, but varies in age from place to place (p. 140, Fig. 56). The lithological characters are therefore of less use than the palæontological for the exact correlation and dating of strata, but have to be employed in the absence of fossils; and in practice the subdivisions used in any district are based on a combination of lithology and fossil-content.

Unconformities, since they represent important events in the history of a district, and since they separate suites of rocks formed at different dates and under different environments, have frequently been employed to delimit the larger groupings of the strata (Fig. 27). But from the point of view of a complete history they fail in this purpose for several reasons.

Thus it has just been pointed out that in different areas the gap represented by the same unconformity begins and ends at different geological horizons, and disappears as the region of continuous sedimentation is approached. But the principal reason is that the very presence of an unconformity implies the absence and destruction of part of the record. To get a complete register we have to search out unbroken sequences of marine bathyal strata (p. 267) that can be made to yield a portion of the standard time-scale (p. 63) which can be used over a large part of the world, and with which can be correlated other sequences less complete or containing fossils belonging to a different facies. In such standard-sequences, for as much as they represent a record of continuous sedimentation and to some extent of continuous organic evolution, the classification of the zones into groups is more or less arbitrary. Sometimes certain zones may be grouped together because they are characterized by the predominance of particular families, orders, or classes of organisms, that are absent or rare outside the limits of the group;[1] sometimes a division may be made at a level where a new type—a so-called *cryptogenic* fossil—suddenly appears: sometimes it is made at a particular zone which in some well-known type-area corresponds to a long-established stratigraphical horizon.

Such a time-scale for the whole geological column is an ideal that has not yet been attained, and is probably unattainable. Only small parts of it have been found and worked out, for example the Graptolite and Ammonite zones (p. 63). In general a much less consistent system of classification has gradually grown up, the basis of which may be briefly outlined. The systems as they have been investigated have been subdivided by reference to their local lithological and palæontological characters, and to the local unconformities.

[1] This is the only really logical scheme of classification, but its use has barely begun yet. As an example note the division of Cambrian time according to faunas into Olenellian, Paradoxidian and Olenian (Table III, p. 69).

The formations and their subdivisions have in this way received names that usually refer to the locality and to the dominant rock-type, e.g. Oxford Clay; or to some fossil or other characteristic, e.g. Nummulite Limestone, Coral Rag, Bunter (= Bright-coloured) Sandstone, Lias (Layers?) Clay. Many of these local and lithological names have by usage acquired a time-significance, and from this point of view should represent a certain complete section of geological time. When employed in this sense the suffix *-ian* is frequently used, e.g. Wenlockian, Oxfordian, Corallian. Unfortunately it has frequently been found that the sequences early investigated and named did not happen to be complete, owing either to non-sequences or to unconformities; or were ill-defined owing to misunderstanding, to the want of fossils or to the presence of igneous rocks. The attempt to retain the well-established names with a revised significance in the light of fresh discoveries has led to much confusion, that is barely lessened when a new name is introduced that is derived from a locality where a fuller sequence has been discovered. This is well exemplified in the Cretaceous where the time-divisions Neocomian, Aptian, Albian, Cenomanian, etc., established on the Continent, sometimes coincide with, but more often straddle, the earlier classic English divisions of Wealden, Greensands, Gault, Chalk, etc.

The following tables show: (II) the nomenclature and the relation between time-divisions and rock-divisions, (III) the principal geological epochs, and the grouping into periods and eras, that is employed in this book.

TABLE II

Time-divisions.	Rock-divisions.
Hemera	Sub-zone or epibole.
Moment or zone-moment	Zone.
Age	Stage.
Epoch	Series.
Period	System.
Era	Group of Systems.

TABLE III

THE GEOLOGICAL COLUMN

Era.	Period.	Epoch.
Cainozoic or Tertiary	Quaternary	Holocene or Recent Pleistocene
	Neogene	Pliocene Miocene
	Palæogene	Oligocene Eocene
Mesozoic or Secondary	Upper Cretaceous	Danian and Mæstrichian Campanian Senonian Turonian Cenomanian Albian
	Lower Cretaceous	Aptian or Vectian Neocomian
	Upper Jurassic	Purbeckian Portlandian Kimmeridgian Corallian Oxfordian
	Middle Jurassic	Bathonian Bajocian
	Lower Jurassic	Liassic Rhaetic
	Triassic	Keuper Muschelkalk Bunter
Palæozoic or Primary	Permian	Thuringian Saxonian Autunian
	Up. Carboniferous	Stephanian Westphalian or Staffordian, Yorkian, Lancastrian
	Low. Carboniferous	Avonian
	Upper Devonian	Famennian Frasnian
	Middle Devonian	Givetian Eifelian
	Lower Devonian	Coblenzian Gedinnian
	Old Red Sandstone Facies	Farlovian, Orcadian, Dittonian, Downtonian
	Silurian	Salopian Valentian
	Ordovician	Ashgillian Caradocian Llandeilian Llanvirnian Arenigian
	Cambrian	Olenian Paradoxidian Olenellian
Pre-Cambrian or Archæan	Proterozoic or newer Pre-Cambrian formations Archæozoic or older Pre-Cambrian formations	

PART II—POST-CARBONIFEROUS SYSTEMS

III. A STUDY OF SEMI-ARID CONTINENTAL ENVIRONMENTS

CHAPTER VI

THE ORIGIN AND NATURE OF THE HERCYNIAN CONTINENT

It has already been explained in the introduction that the "newer rocks" of the geological column on account of their greater simplicity are better fitted than the more ancient systems for a study of the physiographical phenomena of the past. On the usual classification the "newer rocks" are those of the Mesozoic and Cainozoic eras, and the Trias, being the lowest Mesozoic system, is taken as the oldest member of the group (see Table, p. 69); but for the present purpose it is convenient to commence our studies with the uppermost Coal Measure and Permian Formations, because they and the Trias all originated under more or less similar conditions on the surface of a new continent that first began to emerge in Coal Measure times. All three formations are predominantly red rocks that were the products of a semi-arid continental environment. The present chapter is intended as an outline sketch of the events that led up to that geographical setting, followed by a brief résumé of the general conditions governing the formation of these three systems in Britain.

The Altaid Orogeny.—The seas that had overspread much of Britain in Lower Carboniferous times gave place eventually in the Coal Measure epoch to deltas and swampy lagoons. It was during this latter part of the Carboniferous period that great earth-movements set in, which continued intermittently until its close and for long after. The Carbo-Permian times witnessed, in fact, one of the greatest orocratic phases that is known (p. 7). The earth-movements gave rise to the system of mountain-chains which Suess named the *Altaides*. They stretched through Central Europe and Asia. In Europe two important chains can be distinguished: the Armorican, trending from South Ireland through South England,

North-West France and the Central Massif; the Variscan or Hercynian trending from Belgium eastwards through Central Europe (Fig. 28). The term Hercynian is, however, also applied sometimes to the whole of this mountain-system in Europe. At present the stumps of the mountains are largely buried below newer rock, but appear in the European horsts (p. 12 and Figs. 4, 5).

FIG. 28.—Tectonic Units of Europe.

ARM, Armorican; HERC, Hercynian; VAR, Variscan, chains of the Altaides; R.S., Roumanian Spur of the Russian Platform; ZW, Zwischengebirge (Betwixt-Mountains) of Kober. Arrows indicate direction of movement at the surface. (Alpine System after Kober.)

As far as Western Europe is concerned, the uplift of the mountains took place at more than one time, so that it is difficult to generalize; but their first great upheavals were developing in Britain at the time when the Coal Measure swamps and deltas of the Midlands and Northern Britain were disappearing. The earliest movements coincided with and probably produced a change of climate, for the next deposits to be formed in the Midlands bear testimony by their barrenness, composition, and predominantly red colour to a semi-

arid climate very different from that of the preceding Coal Measures. The effect of these late Carboniferous movements was to produce a continent to which is given the name *Hercynia* (Fig. 29). The British Isles, France, Belgium and Germany formed part of it; but it extended to the north-west of the British Isles as an addition to the ancient land-mass (*Atlantis*) over the site of the North Atlantic

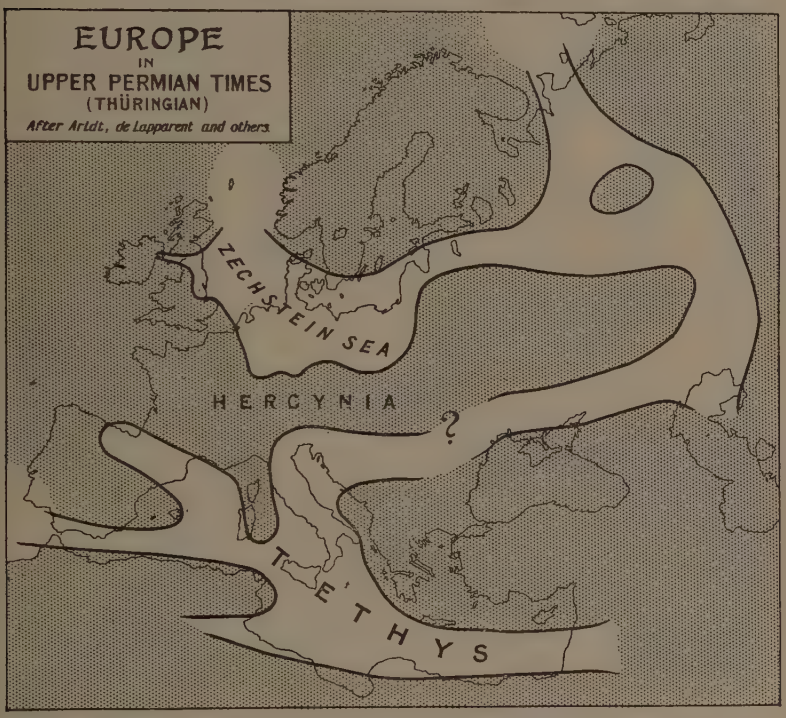


FIG. 29.—Europe in Upper Permian times (Thüringian). (After Arldt, de Lapparent, and others.)

Land stippled.

Ocean, and appears to have been bounded on the east by a sea over the present Ural Mountains, and on the south by the forerunner of the Mediterranean, the sea to which Suess gave the name *Tethys* (see also on p. 105).

It is now proposed to sketch the main features in the development of the portion of Hercynia which lay in the British region with the object of giving the reader a general idea of the geographical environment in which the processes discussed in the next two chapters were working.

That part of the continent of Hercynia which is now North-Western Europe was divisible into two regions with distinctive structures of very different ages [1] (Fig. 28).

(*a*) In the north-west in Scandinavia, Scotland, and probably over much of the North Atlantic, lay the worn-down stumps of mountains that had resulted from a previous orogeny (Caledonian), which long ages before had imparted a general south-west to north-east grain to all the pre-Devonian Formations (Chap. XXII). This region, consisting of rocks already compacted and consolidated, was but little modified by the Altaid Orogeny.

(*b*) To the south-east of the old Caledonian Mountains (Fig. 30), Hercynia owed its configuration primarily to the effects of the Altaid movements which, however, manifested themselves in two different types of crustal deformation. Speaking of similar types in the case of the Alpine Orogeny, the late Grenville Cole has used the apt expressions "*Earth-storm*" and "*Earth-Ground-swell.*" [2] The Altaid earth-storm fell upon Western Europe south of a line passing through the south of Ireland, the extreme south of Wales, the southern counties of England, and into the north-east corner of France and Belgium. This line was the northern boundary of the Armorican ranges, and separated them from the less disturbed region to the north towards which they had been thrust, and which is therefore termed the "*foreland.*" The ranges being within the storm-area, possessed a very complicated structure of overfolds, isoclinal folds, and overthrusts, trending in general from west to east. This structure is found wherever their worn-down stumps can still be seen at the surface (as in South-West Ireland, Cornwall, Brittany). To the north of the line described, the crust of the foreland was rocked by the earth-ground-swell only. In exceptional cases sharp folding took place; but in general the newer Palæozoic strata (Devonian and Carboniferous) were bent into large domes and basins, or broken by faults, many of which register great displacements (p. 89). The region may perhaps have resembled the Basin Ranges country between the Sierra Nevada and the Rockies. As the Devonian and Carboniferous Formations in the foreland overlie a platform of older rocks that had been completely compacted by the Caledonian movements, the axes of the folds and the direction of the faults were probably to a large extent determined by the interaction of the Altaid earth-stresses with pre-existing structures in the platform, though naturally it is rarely possible to elucidate the nature of the interaction. For the present, attention will be

[1] Cf. South America with the ancient massif of the Brazilian Highlands and the new chains of the Andes.

[2] Grenville Cole, *Growth of Europe*, 1914, p. 73.

confined to the structures that have been developed in the Carboniferous strata which, where exposed at the surface, are seen (Figs. 30 and 34) to be folded either along *east to west* axes into synclinal basins, as in the South Wales Coalfield, and into anticlinal domes, as in North Yorkshire; or along *north to south* lines, as in the anti-

FIG. 30.—Tectonic Units in the Altaid Foreland.

SUB, Subsidence; C, Craven Fault; C.F., Charnwood Forest; D, Dent Fault; H.C., Howgill Cleveland; L. Lickey; N, Nuneaton; M, Malvern (mainly inter-Carboniferous); P, Pennine Fault.

cline of the Pennine Chain and in the syncline of the North Wales Coalfield. In addition, folds are found which follow intermediate directions, i.e. *north-west* to *south-east* and *north-east* to *south-west*. Those having north-east to south-west axes, being subparallel to the Caledonian strike that characterizes the under-

lying platform, are usually the more conspicuous. They are well developed in Lancashire, where they are known as the Lancastrian flexures (Jukes-Browne). But in places, especially in the Midlands, the platform had been affected by north-west to south-east disturbances and the Altaid folds then tend to follow that direction.[1]

Professor C. Lapworth [2] gave these four directions of folding (Fig. 31) the following names:

N.–S. . . .	Malvernoid.
E.–W. . . .	Armoricanoid.
S.W.–N.E.	Caledonoid.
S.E.–N.W.	Charnoid.

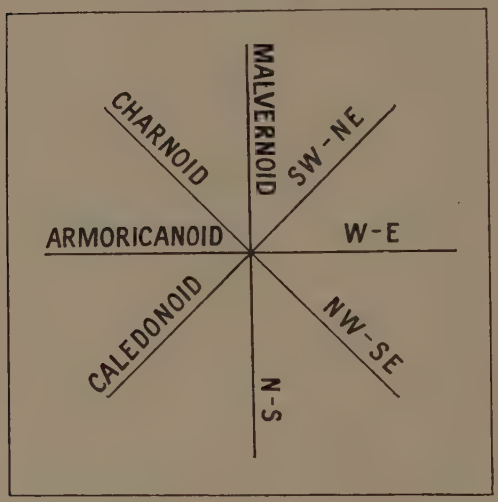


FIG. 31.—Dominant Fold-directions in Britain.

The termination *-oid* shows that direction only is implied, whereas the suffix *-ian* should properly indicate that the fold belonged to the particular orogeny, e.g. "Caledonian" implies a fold produced during the post-Silurian orogeny, but "Caledonoid" refers to a south-west to north-east fold of any age.

As a result of the earth-movements we may picture England as a land-area with the Armorican chains stretching across its southernmost portion and with the remainder constituting a foreland of

[1] The Yorkshire Coalfield is also best regarded as a syncline with a N.N.W.–S.S.E. axis. W. G. Fearnsides, *Trans. Inst. Mining Eng.*, vol. xi, 1916, pp. 409–455.

[2] *Rep. Brit. Assoc.* for 1913, 1914, p. 598.

bold foothills trending east-west and north-south, with lesser ridges and faulted blocks in various other directions.

From Carboniferous times through the Permian and Triassic periods North-Western, Western and Central Europe remained continental. There were, however, large depressions or intermontane basins in which considerable thicknesses of sediment accumulated in lakes or on delta-fans and alluvial plains. At times also the sea advanced and covered Germany and parts of what is now the North Sea and North-East England. Since it is the deposits left in these depressions that give us the history of this long period, more will have to be said later (pp. 79–81) about their locations and shapes, and the nature of the bodies of water that occupied them. We must, however, bear in mind that a large proportion of the continent was at first mountainous, and even when the mountains had become greatly denuded, there were vast stretches of country where erosion and not deposition were going on. Judging from the nature of the deposits, the climate throughout these periods was a continental one resembling that of the centre of Asia to-day.

There is a good deal of controversy over the age and mutual relationship of the rocks that were formed on this continent. Having been laid down partly on land, partly in lakes and partly in arms of inland seas, most of them are unfossiliferous; and those that contain organic remains represent a variety of different specialized environments, so that the fossils are of little value for correlation purposes.

The rocks are usually regarded as belonging to three separate systems:

Trias,
Permian,
Uppermost Carboniferous (Upper Coal Measures),

but recent work suggests that in reality the so-called Permian red rocks belong to the Carboniferous, whereas the so-called Upper Permian Magnesian Limestone is Triassic in age.[1] This view, which does away with the Permian System altogether, is not generally accepted; and we shall here follow the usual classification, because by so doing we shall enable the reader more readily to correlate the processes discussed with the stratigraphical descriptions to be found in other works. Table IV gives an outline classification of the rocks as exposed in the four principal developments. Correlation from column to column is not intended, save in a very general way.

[1] A full discussion of the classification and correlation of the rocks formed between the Coal Measure and Jurassic periods will be found in R. L. Sherlock's "A Correlation of the British Permo-Triassic Rocks," *P.G.A.*, vol. xxxvii, 1926, pp. 1–72, and vol. xxxix, 1928, pp. 49–95.

TABLE IV

	S.W. Cuvette.	Central Midland Cuvette.	N.W. Cuvette.	N.E. Cuvette.
Usually classed as Trias	Keuper Marls, red and green marls with gypsum	Keuper Marls, red and green marls with salt and gypsum and a band of grey sandstone	Keuper (Stanwix) Marls, red marls with gypsum and/or rock-salt	Red marls
	Keuper Sandstone, red and grey sandstones	Keuper Sandstone, red and grey sandstone		
	Bunter, coarse red sandstone	Bunter, Upper Mottled Sandstones	Kirklinton Sandstone, red sandstones	Red sandstones and pebble beds
	Budleigh Salterton Pebble Bed	Pebble Beds, Lower Mottled Sandstones	St. Bees sandstone, red sandstones with small local conglomerates	
Usually classed as Permian	Red marls	Unconformity	Gypsiferous red marls	Saliferous red marls
		Enville Marls, red marls	"Magnesian Limestone," dolomites	"Magnesian Limestone," dolomites, limestone, anhydrite, gypsum and salt
	Red sandstones	"Trappoid" breccias of Clent, Nechells, Warley, etc.		
	Red conglomerates and breccia		Plant-bearing shales	"Marl Slate"
	Red clay		Penrith Sandstone, red sandstones and breccias known as "brockrams" [1]	Quicksands and breccias
	Unconformity	? Unconformity	Unconformity	Unconformity
Usually classed as Upper Coal Measures (Carboniferous)		Enville Beds, red marls, sandstones, and calcareous conglomerates.		
	?	Keele Beds, red marls, sandstones, cornstones, and "Spirorbis limestones."		
	Upper Productive Coal Measures of Radstock and Bristol Coalfields.	Newcastle Beds, grey sandstones, marls, coals, and "Spirorbis limestones."		
		Etruria Beds, purple and mottled marls, sandstones and green breccias ("Espley rocks").	Whitehaven, Sandstones, mostly red measures	

[1] Similar breccias occur locally at higher levels (see p. 92).

We must not think of the uplift of the Hercynian continent as completed before the agents of denudation had commenced their attack. Uplift, erosion and deposition were going on simultaneously, now one, now another of the three processes predominating in any given region. As already pointed out, the products of the denudation of this continental mass accumulated for the most part in intermontane basins without outlet to the sea, but in North England at times the sea encroached on to two of the depressions. Each of these areas where sedimentation was proceeding may be conveniently termed a *cuvette* or basin of sedimentation.[1]

As already mentioned, the semi-arid continental conditions first supervened at the end of Coal Measure times when earth-movements began in the Malvern district along the Welsh Marches, and in Cumberland. Ordinary productive coal measures were being laid down in South Wales, Gloucestershire and Somerset in freshwater delta-swamps (Plate I, B), but in the Midlands and farther north predominantly red rocks were being deposited in a separate basin, possibly devoid of outlet to the sea. The strata are mostly red marls, but sandstones, breccias and conglomerates also occur, and at times even normal productive Coal Measure rock-types. It is probable that considerable mountains were being elevated (the Mercian Highlands and Wales, p. 82) in the regions surrounding the basin, and perhaps the main Armorican folding of South England may belong to about this time. It was these surrounding areas that supplied the material for the deposits of this *Midland Cuvette* (Fig. 32). In what has usually been regarded as Permian times some movement recurred within the cuvette itself, for some of the higher breccias (Clent, Warley, etc.) appear to rest on the denuded edges of the older formations. Finally great movements supervened and the basin was broken up into separate depressions by desert hills. The Triassic rocks that follow, lie over and bury this desert land-surface, having been deposited first in the hollows and later, as the hills were levelled, spreading over the lower parts of an undulating country. The rocks are wind-blown sand- and dust-deposits; the sands, gravels and breccias thrown down by torrential rivers, sometimes on delta-fans, sometimes in lakes; and the chemical precipitates of salt lakes.

The Midland basin in so-called Permian times passed northwards

[1] *Cuvette* is a convenient term for a basin in which sedimentation is going on (German, *Sammelmulde*), as distinct from a tectonic *basin* due to folding of pre-existing rocks, and not necessarily basin-shaped as far as the present structure is concerned, e.g. the Anglo-Parisian cuvette was the region in which the Lower Cainozoic rocks of Britain and North France accumulated. It is now folded into a number of basins—Paris, Hampshire, and London Basins.

into a *North-Westerly* Cuvette in Lancashire, Cumberland, South-West Scotland and the adjoining parts of the Irish Sea; and into a *North-Easterly* Cuvette in Nottinghamshire, Yorkshire and Durham,

FIG. 32.—Late-Permian Geography, based on Stamp and Sherlock.
Unstippled parts, areas of deposition.
It is probable that the Lake District was never under the waters of the Zechstein Sea, as shown in Sherlock's map.

the two basins being separated by the embryonic upfold of the Pennines (Fig. 32). It is not clear how far the deposits in these two areas were contemporary with one another and with those of the Midlands; but it is probable that to some degree each had an independent history.

In the *North-Western Cuvette* (p. 88) there are great thicknesses of desert sandstones, breccias and marls; and intercalated locally towards the middle of the Permo-Triassic succession is a thin representative of the Magnesian Limestone which forms the lower part of the Permo-Triassic succession in the North-Eastern Cuvette (pp. 92, 94). It is evident that with the exception of this marine invasion the north-western basin was one of internal drainage, probably throughout Permian and Triassic times, the sediments accumulating in it being either wind-borne or else the products of temporary torrents and lakes.

The *North-Eastern Cuvette* differs from the others in that its surface had been levelled to a plain, and this plain was then invaded from the east by a sea which spread over Germany and there laid down the limestones known as the Zechstein (Fig. 29). In England the deposits are termed the Magnesian Limestone Series (p. 95), and consist mainly of dolomites, limestones, and some marls, with intercalations of anhydrite, gypsum, and rock-salt. The rocks agree closely in composition and fossils with the Zechstein limestones, and there is no doubt that both were deposited in a more or less land-locked sea which at times dwindled to a number of salt-lakes where chemical deposits were finally thrown down (p. 98).

The Magnesian Limestone is followed in North-East England without any break by red sandstones and marls of the usual Triassic type; and the region must by then have presented an environment very similar to that prevailing in the other cuvettes with which it was also confluent.

There were two other basins of deposition: one, of which little is known but which has yielded remains of some very interesting land-animals, lay in the *Moray Firth region*; the other was within the limits of the Armorican chains in *Devon and Somerset*, but did not come into existence until these chains had been almost levelled off by erosion. The Devon-Somerset or *South-Western Cuvette* received sands, conglomerates and breccias very similar in appearance and origin to those of the Midlands.

We can therefore in so-called Permo-Triassic times recognize five basins (Fig. 32), each with a more or less independent history, viz.:

South-western Cuvette.
Midland Cuvette.
North-western Cuvette.
North-eastern Cuvette.
Moray Firth Cuvette.

They agree, however, in that they gradually became filled up, the sediments becoming finer and extending over wider areas as time went on, a fact that implies the gradual levelling of the surrounding

highlands. These relations are expressed by the extension of the newer rocks (especially in the Trias) beyond the boundaries of the original basins, so that they rest in many parts not on the older members of the Permo-Triassic sequence, but upon the Carboniferous and still more ancient strata (p. 108). By this gradual levelling of the hills and extension of the areas of sedimentation, most of England was by the end of Triassic times a great plain on which, perhaps in temporary lakes or in more permanent sheets of shallow salt water, the Keuper Marls were deposited. The upstanding areas where deposition was not going on, were limited to three main regions (Fig. 32) that may be termed:

1. The *Northern Massif*, over Scotland, probably connected by way of the ancient Atlantic continent (p. 73) with

2. The *Western Massif*, over Wales, Ireland, parts of the Irish Sea and Cornwall.

3. The *Eastern Massif* over the Lower Thames Basin, East Anglia, North-East France and Belgium. In Carboniferous and Permian times a north-westerly extension into the South-East Midlands is known as the Mercian Highlands (Fig. 32).

These three massifs exerted an important influence on the geographical development of the British region throughout the rest of Mesozoic times and will be repeatedly referred to.

CHAPTER VII

THE RED UPPER COAL MEASURES AND RED "PERMIAN" ROCKS

Classification (see p. 77).—It is clear from Table IV (p. 78) that the rocks deposited in Britain [1] during the late Carboniferous and Permian periods are predominantly red-coloured breccias, sandstones and marls, usually devoid of fossils; but that in Northern England dolomites and chemical precipitates also occur.

In Devonshire and South-Western and Central Scotland contemporary igneous rocks are found, showing that a number of active volcanoes were in operation, some of which rose out of lakes as islands.

Modern Deserts.—In semi-arid and arid regions to-day (see p. 27) the supply of coarsely broken rock often exceeds the capacity of the transporting agencies. The largest blocks are left behind to form screes on the hill-sides, while the smaller material may be carried by torrential floods a short distance from its source, and be deposited in temporary lakes or on the plains to form deltas or alluvial cones and fans. The coarser part of this material may be angular or rounded according to the distance it has travelled in the rivers. The finer may be sand, mud or dust. Chemical precipitates also may be expected in and around large lakes that, like the Dead Sea or the Great Salt Lake, have no outlet and are subjected to great evaporation, and in smaller and more ephemeral pans and playas (p. 43). Apart from these water-laid deposits, sand-dunes and loess may accumulate on dry land (p. 40).

The Aralo-Caspian basin, together with North Persia and Turkistan, offers many features for comparison with the late Carboniferous and Permian geography of North-West Europe. Here is a desert in which mountains girdle the southern margin of a wide, flat, wind-swept basin, exposed to an enormous annual and, in summer, a great diurnal range of temperature. In the mountain-tracts huge cones of angular debris bury the lower slopes. A low rainfall in the hills and the melting of the winter snow in the mountains feed rivers which either die away on the edge of the plains in

[1] Except South Wales, Bristol and Somerset, where the uppermost Coal Measures are of the "productive" type (Plate I, B).

the sands and gravels that they themselves have brought down through the ages; or in the case of the larger rivers (Syr-Darya and Amu-Darya) throw down mighty deltas [1] in the brackish waters of the Sea of Aral that covers the lowest part of the basin. In the dry seasons the rivers tend to block their own channels with detritus, and therefore frequently change their courses. The Amu-Darya, for instance, in the times of the Greek historians flowed to the Caspian.

Blanford [2] long ago described the present-day formation of *delta-fans* [3] on the southern fringe of this great desert. In spring the

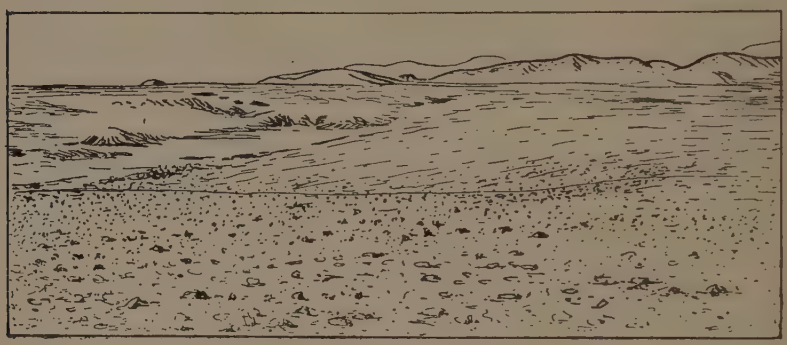


FIG. 33.—Amotape Breccia-fan, Peru, looking north-eastwards two miles from the mountains.

A water-course on left and in the central middle distance is dissecting the fan. (From a photo by T. O. Bosworth.)

rivers, swollen by the melting snow, bring down in their flooded streams the angular detritus that has been riven by sun, frost and temperature-changes from the bare hills, and thus build up vast sheets of ill-assorted and poorly-rounded rock-waste in the neighbouring valleys and lowlands.

The Caspian Sea and the Sea of Aral have fluctuated greatly in area in the past. At the present time, the salinity of these sheets of water varies according to the amount of inflow and of evaporation both seasonally and from place to place, so that in one part of the Caspian practically freshwater deposits are being laid down, while

[1] The delta of the Syr-Darya increased by 13¾ square miles between 1847 and 1900.

[2] *Q.J.G.S.*, vol. xxix, 1873, p. 496.

[3] In later years Bosworth has given an excellent description of the great breccia-fans (Fig. 33) of the desert of Tumbes in Peru, torrent-laid deposits in one of the driest regions of the world, where rain falls perhaps once in ten years. T. O. Bosworth, *Geol. and Palæont. of N.W. Peru*, chap. xlii, London, 1922.

in another the bottom over an area of 1,300 square miles is composed of a layer of Epsom Salts ($MgSO_4$) as much as 7 feet in thickness.[1] The latter has been deposited from a supersaturated solution in a land-locked bay that is subjected to intense evaporation during the summer.

Having introduced the reader to a very distinctive type of physiographical environment, we may now examine the deposits of the Upper Coal Measures and Permian with a view to seeing how far they afford a record of similar conditions in Britain during the time of their formation.

The red colour of these rocks and of the Trias is very striking, and is usually regarded as indicative of a desert origin.[2] It is due to the coating over of the particles comprising the sediments by a film of red oxide of iron, a characteristic said to be due to the absence from desert waters of organic acids that elsewhere are normally present and act as reducing agents.

Marls are the most characteristic rock-type in the Upper Coal Measures, and occur in the Permian also; and though the particles forming them may have originated as dust, these rocks are usually water-laid.

The desert-nature of the lakes or playas in which these red rocks originated can be demonstrated in some cases by the preservation of footprints and sun-cracks, and the imprints of rain-drops. All of these denote the drying up of the water and the baking of the mud; but though these features were recorded on the mud, it is in the form of natural casts in sandstone that they are usually found. The method of preservation in the three cases can readily be understood from an explanation of fossil-footprints. An animal walked on the half-dry mud and left impressions of its footmarks. The mud was then baked hard by the sun, and at a later date sand, either blown or washed over the hardened surface, filled up the impressions. The sand has now become cemented to a sandstone and preserves on its under-surface natural casts of the footprints. It is these, and not the actual imprints that are found. The fact that in certain beds a large number of different creatures can be proved by their footprints to have been simultaneously in existence, though not one is known

[1] Spindler in *Izvestia Russ. Geogr. Soc.*, vol. xxxiv, quoted in *Enc. Brit.*, XI, Edition 1911, vol. v, p. 454. See also E. Haug, *Traité*, vol. i, p. 100.

[2] It is significant, however, that modern deserts are usually characterized by browns, not reds. Where red is dominant it appears to be connected with the derivation of the surface material from laterites (p. 26) that are the tropical weathering product of basic igneous rocks (J. Walther, *Gesetz der Wüstenbildung*, 4th edit., 1924, pp. 293–4). The widespread lavas poured out by the Carboniferous volcanoes (p. 313) may have therefore contributed to the redness of the deposits under consideration.

from fossilized bones or teeth, is an interesting commentary on the chance that terrestrial organisms have of preservation as fossils. It warns us also against concluding from the absence of fossils that the rocks were formed in an utter desert.

The drying up of mud flats is also recorded in another way. There are in the Upper Coal Measures "pellet rocks" in which flakes of marl occur as pebbles set in a matrix, and "cornstones" in which chips of limestone [1] make up the bulk of the material. In each of these cases it is clear that newly-formed sediment had been dried and broken up by alternate heat and cold, and then carried away by wind and water to be incorporated in another deposit forming near by. Further reference will be made to this feature of a semi-arid environment in the sequel (p. 114).

Method of Formation of the Breccias.

Considerable uncertainty still prevails as to the age of some of the sedimentary breccias [2] found in the South-Western, the Midland and the North-Western cuvettes. The majority are late Carboniferous or Permian, but some are entirely Triassic in age (p. 92).

The breccias consist of roughly-stratified beds of coarse or fine angular fragments of older rocks united in a marly or sandy matrix, sometimes loose, sometimes cemented by lime into a hard rock. They represent more or less consolidated delta-fan deposits formed under semi-arid conditions from the local scree-material which was riven by the agents of erosion from the desert-surfaces of the Permian landscape.

South-Western Cuvette.—(Fig. 32). Here it is found that the breccia-formation rests on a surface cut in the Devonian rocks, and is "a congeries of more or less local deposits, for the most part of rock-fragments, in the form of angular debris, boulders, gravel and coarse sand, washed down from neighbouring slopes and valleys into a lacustrine area of deposition." [3] The breccias change rapidly both vertically and laterally into sandstones or marls. Each individual bed is markedly lenticular, as might be expected if each lens represents the product of a single flood. The coarsest material would be thrown down near the mouth of a mountain-valley, whereas

[1] The so-called Spirorbis limestones are thin fine-textured limestones containing the small spiral worm-tube known as *Spirorbis*. They are probably inorganic precipitates of lime formed on the floor of shallow sheets of evaporating water, and are a characteristic feature of the Upper Coal Measures.

[2] W. S. Boulton, *Q.J.G.S.*, vol. lxxx, 1924, pp. 343–65. See also T. H. Whitehead and T. Eastwood, "Geol. of Southern Part of South Staffs Coalfield," *Mem. Geol. Surv.*, 1927, pp. 133–7.

[3] A. J. Jukes-Browne, *Building of the British Isles*, 4th edit., London, 1922, p. 196.

the sand and mud would be carried farther away. The next flood would repeat the process, but its deposits would not occupy exactly the same positions as did the first. Often also a flood would wash away parts of previous deltas.

The blocks forming the Devonshire breccias vary in size up to a diameter of 4 or 5 feet. From a study of them it is possible to deduce something of the geological structure of the surrounding country at the time of their formation. In the lowest part of the series Devonian rocks, similar to those on which the lower breccia lies, form the bulk of the fragments; but at the time of the formation of the upper breccias the great Dartmoor granite (of Carboniferous age) had been bared of its thick cover; for in them are found fragments of granite and of quartz porphyry.[1] The latter appear to have been derived from minor intrusions and perhaps from volcanoes that surmounted or were associated with the granite batholith. The pebbles and sand grains in fact constitute the sole evidence preserved to us of the existence of these volcanoes. These vents must not be confused with others near Exeter, known from their lava-flows which are intercalated in the lowest Permian sediments. The Exeter lavas also contributed fragments to the breccias.

As the degradation of the neighbouring highlands proceeded, the supply of coarse material diminished, and the highest part of the breccia formation is found to merge upwards into sandstone and marls with intercalated conglomerates.

The Midland Breccias.—In the Midlands the "Mercian Highlands" (Fig. 32) (see p. 82) came into existence long before the Permian, and we see their influence throughout the Carboniferous and Permian. The so-called "trappoid" breccias are found from Malvern to Wolverhampton.[2] They had an origin similar to those of Devon and Somerset. Below them, sometimes classed as Permian, but probably more correctly regarded as Carboniferous in age, is a conglomerate-formation known as the "Calcareous Conglomerate." Wickham King has pointed out that the materials both of the conglomerates and of the breccias are derived from the Mercian Highlands, but the former contains pebbles of Carboniferous, Devonian and Upper Silurian rocks, while the breccias overlying them obtained their constituents from still older formations. Just as in Devon, therefore, these fragmental rocks provide

[1] See A. J. Jukes-Browne, *op. cit.*, 1922, p. 197, and *Stratigraphical Geol.*, 2nd edit., 1922, p. 333; but A. W. Groves, *Proc. Geol. Soc.*, 1929, No. 1197, p. 72, states that "the minor intrusions above the granite were being rapidly eroded in Permo-Triassic times, but there is no evidence [from the mineral assemblage in the sands] of the actual granite being exposed at that period."

[2] W. W. King, *Q.J.G.S.*, 1899, p. 97. W. S. Boulton, *Q.J.G.S.*, 1924, p. 343.

a record of the gradual denudation of the highlands, by which older and older formations were exposed to desert-weathering and added their screes to the deposits of the intermontane cuvette. The associated sandstones and marls interbedded with the breccias may well have originated like those of the Upper Coal Measures, from sand and dust partly washed and partly blown into temporary lakes.

The Deposits of the North-Western Cuvette.

The north-western area of Permian deposition lay in Lancashire, Cumberland, Westmorland, and parts of Yorkshire, of Scotland, the Isle of Man, and Ireland (Fig. 32). As typically developed

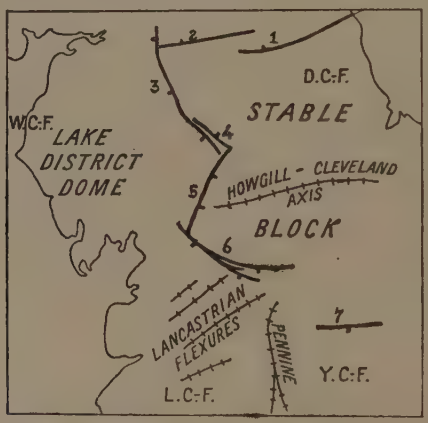


FIG. 34.—Northumbrian Fault-System. (Pre-Permian, except perhaps 1, 2, and 3).

1, Tynemouth; 2, Stublick; 3, Outer Pennine; 4, Inner Pennine; 5, Dent; 6, Craven; 7, Leeds, Faults. Crossed lines are anticlinal axes. W.C.-F. Whitehaven, D.C.-F. Durham, L.C.-F. Lancashire, Y.C.-F. Yorkshire, Coalfields.

in the Eden Valley there are two divisions of the Permian: an upper one with shale, red clay and magnesian limestone, and a lower (Penrith Sandstone) with bright red or variegated sandstones, which contains two thick bands of breccia, known locally as "Brockrams," the fragments in which are mainly derived from the neighbouring Carboniferous Limestone. The Penrith Sandstone is a mass of wind-blown sand, a thousand feet thick, built up of well-rounded grains of quartz that resemble the sand-grains produced in deserts by the action of the wind. There are also abundant grains of felspar, a mineral that under normal moist climates weathers to a clay. Its presence is therefore suggestive of mechanical shattering under a dry climate (p. 27).

According to Prof. P. F. Kendall and others the borders of the North-Western Cuvette can be studied in north-west Yorkshire and on the flanks of the Vale of Eden, where the Pennines rose as

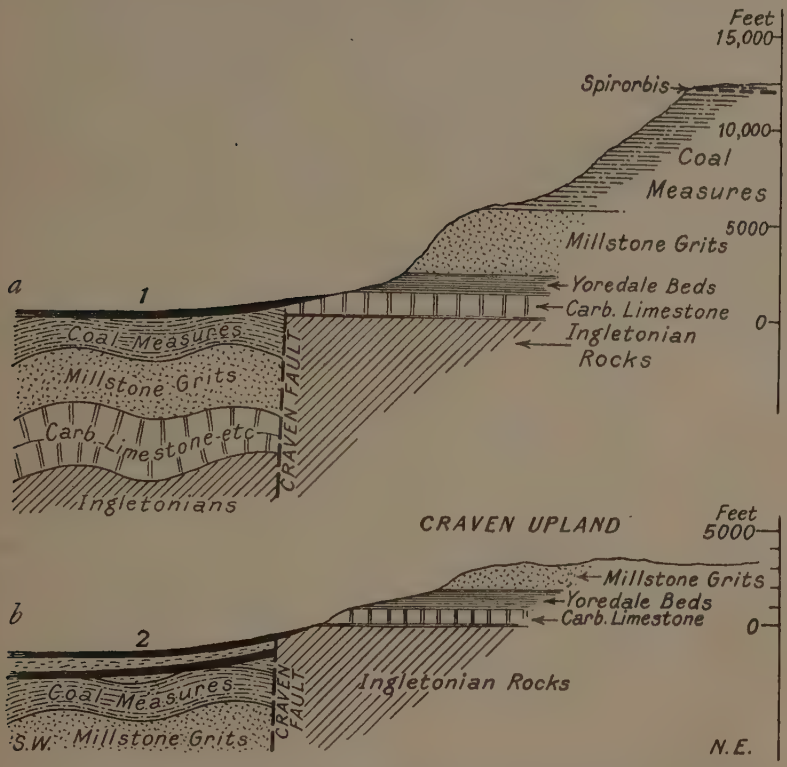


FIG. 35.—Diagrammatic sections across the Ingleton District in Permian times; to illustrate pre-Permian faulting renewed during Permian times; formation of Breccia-fans (1 and 2) at two dates, with renewal of faulting in between; and the great erosion of the Craven Upland.

Vertical scale only approximate. Datum-level is the base of the Carboniferous, north of the fault.

"block-mountains" or plateaux bounded on the west and south by mighty scarps that marked the positions of faults (Pennine, Dent, Craven) separating the uplifted from the depressed areas (Figs. 34, 35). The breccias or brockrams are the reassorted screes, washed from the cliffs and redeposited in the depressed region to the west.[1] There seems some doubt about the accuracy of this

[1] P. F. Kendall and H. E. Wroot, *G. of Y.*, chap. xxv.

conception as regards the northern part (see p. 91), but the Ingleborough area with its bounding Craven fault-system appears to bear out the theory.

The fault-scarps separating the various plateaux of Arizona provide a very instructive analogy in this connection.[1] After describing the "Hurricane Ledge" between the Uinkaret and the Sheavwits plateaux, W. M. Davis writes: "The western boundary of the Sheavwits is another ragged west-facing cliff, 2,000 or 3,000 feet high, and so bold that it provokes rainfall. . . . Great volumes of rock-waste have been washed down from this bold escarpment upon the lower land, to which the name of "Grand Wash" is therefore given; and the ragged bluffs of the escarpment are called the Grand Wash cliffs. . . . Where the river [Colorado] cuts the base of the Grand Wash cliffs, the fracture by which the upper and lower blocks are displaced may be discovered on the valley sides." The debris of the Grand Wash is a present-day equivalent of the brockrams.

Enormous erosion of the Carboniferous and Pre-Carboniferous rocks went on before and during the deposition of Permian rocks in the north-western region. This can be seen from the fact that the Permian strata rest on and against very different horizons within the older series, in many cases on those that can be shown to have once been deeply covered by Carboniferous strata, and by the fact that the lower breccias consist of fragments of the higher Carboniferous formations (Fig. 35*a*), while the upper breccias contain material from the basal beds of the Carboniferous and from even older rocks (Fig. 35*b*) in the Ingleton district. Prof. Kendall considers that as much as 5,000 feet of rock was removed. There is good evidence that the uplift of the range was going on concurrently with this denudation, being largely accomplished by repeated movement along the Craven Fault.

The picture that Prof. Kendall draws of the Pennine area of North-west Yorkshire and Westmorland in Permian times depicts a veritable desert: "a country of high, barren, stony waste, with crumbling mounds of shale, sandstone scars and terraces of limestone. This stony waste would be terminated by the great fault scarp [of the Dent and Craven fault-system] fretted along its margin by deep, rocky khors or wadies down which, from time to time, torrential rains, such as those that visit at infrequent intervals the similar regions to-day, would send torrents of water sweeping the sun-splintered rock-fragments from their floors out into the low grounds. To the westward would stretch the tawny sands of a wide desert-expanse unbroken save perhaps by the hills of the Silurian tract about the

[1] W. M. Davis, *Physical Geography*, London, 1901, pp. 155–7.

Lune, the Lake Country, and in the dim distance the mountainous group of the Isle of Man." [1] It seems legitimate to assume, however, that, at any rate at times, the lower parts of the western desert-expanse were flooded to form lakes or temporary sheets of water (playas), for some of the sediments show signs of having been accumulated under water. Thus they are often current-bedded, the westerly dip of the layers suggesting an easterly origin of the material. Both in the Vale of Eden and in the Scottish extensions of this north-western basin of Permian deposition, some of the red sandstones yield casts of the footprints of various Amphibians. At a slightly later date than Penrith Sandstone times, the Zechstein Sea also found its way from Yorkshire into the north-western basin, as is recorded by a thin equivalent of part of the Magnesian Limestone of the North-Eastern Cuvette.

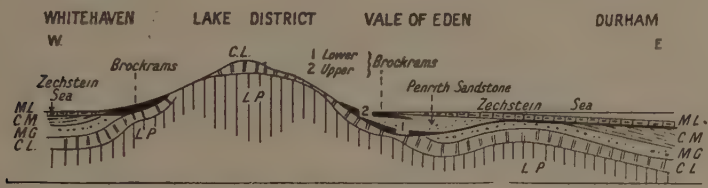


FIG. 36.—Diagrammatic section from Whitehaven to Durham; to show the relationship of the Brockrams to the Carboniferous and earlier rocks of the Lake District and to the Magnesian Limestone of the Zechstein Sea, in Lower Magnesian Limestone times, incorporating the views of the Geological Survey at Whitehaven, and of J. S. Turner in Vale of Eden.

ML., Magnesium Limestone; C.M., Coal Measures; M.G., Millstone Grit; C.L., Carboniferous Limestone; L.P., Lower Palæozoics.

The views expressed by Prof. Kendall and summarized above have been recently challenged, as far as the Vale of Eden is concerned, by Mr. J. S. Turner.[2] He claims to have shown that the Lake District had been uplifted in pre-Permian times, and that the Brockrams of the Vale of Eden on the east and those of the Cumberland Coalfield on the west, were derived from the denudation of the Carboniferous covering of the Lake District (Fig. 36). This conclusion is based chiefly on the demonstration that the Dent and Pennine faults had a down-throw to the east in Permian times,

[1] P. F. Kendall, *Proc. Geol. Assoc.*, vol. xxii, 1911, p. 49.

[2] J. S. Turner, *P.G.A.*, vol. xxxviii, 1927, pp. 339–74. Some of Turner's conclusions are supported by the work of F. M. Trotter and S. E. Hollingworth, *Geol. Mag.*, 1928, pp. 433–48, who show that the elevation of the northern end of the rigid block now outlined by the Stublick, Pennine and Dent fault-system, was depressed, not elevated, in Permo-Triassic times, as postulated by Kendall. See Fig. 34.

not to the west as at present. If this is true, the comparison with the fault-scarps of Arizona fails as far as the Vale of Eden is concerned; though the general desert-conditions and the torrential deposition of the Brockrams remain uncontested, and the comparison still holds good for the Ingleton district (Craven Fault) (Figs. 35*a* and *b*).

That the desert-state of this northern region persisted for a long time is evidenced by the very different horizons at which the breccias or brockrams are found. Thus in the Vale of Eden there are two

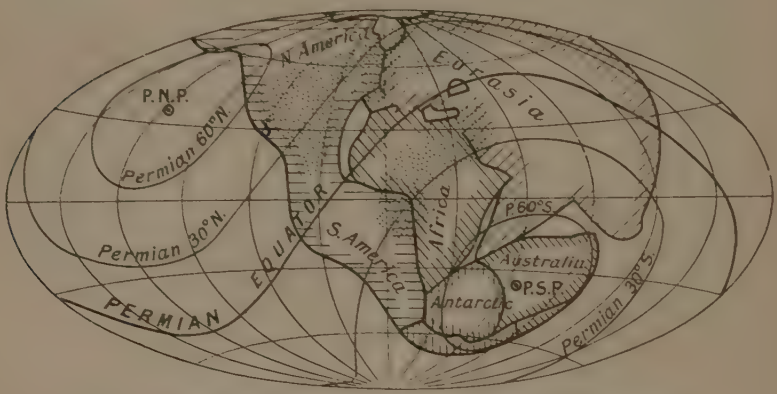


FIG. 37.—Permian Geography, based on Köppen or Wegener.
Stippled areas, tropical dry belts in Permian times; P.N.P. and P.S.P., Permian North and South Poles.

main bands, separated by perhaps 1,000 feet of Penrith Sandstone. The higher one lies well below the Magnesian Limestone (Thuringian). In West Cumberland Dr. Bernard Smith [1] has shown that while some of the breccias also underlie the Limestone, others pass laterally into it, and yet others overlie it. Further, they are found in the neighbourhood to pass laterally into still younger shales and sandstones that probably are Triassic in age. If this be the case, breccia-forming conditions persisted in North England throughout the whole of the time embraced by the British Permian and Bunter periods. This fact emphasizes the difficulty of separating the New Red Sandstone Formation of the North Country into its component Permian and Triassic Series.

From a consideration of the three cuvettes just dealt with, there

[1] B. Smith, *Geol. Mag.*, 1924, p. 209. This paper includes a valuable comparison with regions where similar breccia-formation is going on to-day or has gone on in recent times.

is strong presumptive evidence that England was virtually a desert in late-Carboniferous and Permian times.

The desert-belts of to-day are so exclusively confined to the tropics that it is justifiable to argue, as does Prof. Kendall, that the Permian deserts also lay in those zones. This view has also been advocated by Wegener and others. If this be true, it follows that the equator during that period lay in a position markedly different from its present location [1] (Fig. 37).

The North-Western Cuvette was the scene of considerable volcanic activity. Numerous vents in Nithsdale, Annandale, and Ayrshire are proved to belong to the Permian period by the fact that the material filling the vents, and the lavas and tuffs thrown out from them, are interbedded with and covered by red sandstones demonstrably of that age. This implies that the outpourings at this centre took place in or around the lakes which occupied the valleys and hollows in the surface of the cuvette (p. 347).

Another group of some eighty volcanoes found in East Fife is also regarded as Permian in age (pp. 347–50).

[1] P. F. Kendall and H. E. Wroot, *Geol. of Yorkshire*, p. 260. A. Wegener, *Origin of Continents and Oceans*, p. 105. W. Köppen and A. Wegener, *Klimate der Geol. Verzeit.*, 1924, p. 23.

CHAPTER VIII

THE MARINE UPPER PERMIAN OF NORTH-EAST ENGLAND

The Unconformity below the Marine Permian.—In the north-eastern region enormous erosion accompanied and followed the uplift of the Hercynian Continent. The Carboniferous rocks had been folded into the north-south Pennine flexure, and into the west-east Howgill-Cleveland upfold through North Yorkshire.

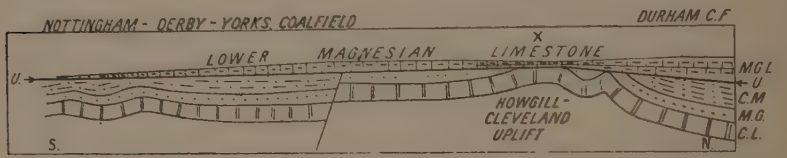


FIG. 38.—Diagram-section of the Unconformity below the Magnesian Limestone in N.E. England.

Note apparent conformity at X. M.G.L., Lower Magnesian Limestone; U, Unconformity; C.M., Coal Measures; M.G., Millstone Grit; C.L., Carboniferous Limestone.

The latter fold was planed down to the extent of several thousand feet, until the Coal Measures, the Millstone Grit, and much of the Carboniferous Limestone had been removed from its axis north of Richmond, Yorks (Figs. 34, 38). The denudation had been so complete that the country had been reduced to the condition of a great plain before the epeirogenic depression occurred which admitted to our North-Eastern Cuvette the waters of the German Zechstein Sea in which the Magnesian Limestone Series was deposited. Even at this stage, the Pennine Chain persisted as a barrier across which the sea only passed for a short time through one or more devious channels. When this occurred the north-western basin became temporarily a land-locked gulf whose western shores lay in Ireland (see p. 91 and note on Fig. 32).

In the North-Eastern Cuvette therefore as a result of *orogenic* uplift, followed by prolonged denudation and eventually by widespread *epeirogenic* depression, all the criteria were present for producing an *unconformity of Type* 1 (see p. 65) in which the newer and unconformable series lies on a nearly plane surface without rapid

overlap of the higher strata beyond the lower members of the new series. Such an unconformity often involves, as it does here, a relation of the two series which is expressed by the term "*overstep.*" By this is meant that the newer unconformable series, when traced laterally, is seen to rest first upon one and then upon another formation of the older series. The way in which the Permian oversteps the different subdivisions of the Carboniferous may be seen on any geological map of North-East England, and is shown in section in Fig. 38.

At the present time, owing to an easterly tilting of the Permian, the sub-Permian floor slopes to the east, at a very low angle, and it is so uniform in Yorkshire and Nottinghamshire that the depth at which it may be met can be foretold with great accuracy by interpolation between known points and by extrapolation beyond the limits so far explored. Since the floor over large areas consists of coal-bearing rocks this feature is one of considerable economic value.

The Sequence.—The Magnesian Limestone Series of the North-Eastern Cuvette consists predominantly of dolomites, dolomitic limestones and shales, true limestones, and red marls; but locally considerable bands of sandstone appear, as at Mansfield, and at many points there are basal breccias and sands. Anhydrite, gypsum, and rock-salt are occasionally associated both with the marls and with the limestones, sometimes in very thick masses. The whole series is generally regarded as Upper Permian (Thuringian) in age, but Sherlock has urged the inclusion of it and of the German equivalent [1] in the Trias.

It is the peculiar products of the Zechstein sea and the salt-lakes which grew out of it that interest us here rather than their exact age, but it should be noted that there is no real break between the "Permian" deposits and the "Triassic" red sandstones, pebble beds, and marls which follow it and into which it may pass laterally.

Table V gives the general sequence as observed at outcrop in Nottinghamshire, Yorkshire, and Durham. It will be seen that there is considerable lateral variation in the subdivisions as traced from Durham to Nottinghamshire, only the "Lower Limestone" persisting throughout. Fig. 39 (adapted from Sherlock's paper) shows diagrammatically the changes of lithology. If we take the limestones to indicate marine conditions and marls to denote salt-marsh environments, it is clear that the southern seashore was at times near Nottingham, and at other times retreated to the north; whereas the sea or salt-lakes (indicated by dolomite, salt, and anhydrite) persisted continuously in the extreme north. According to

[1] R. L. Sherlock, *Q.J.G.S.*, vol. lxvii, 1911, pp. 75–117; and *P.G.A.*, vol. xxxvii, 1926, pp. 1–72.

TABLE V

Germany.	Durham.	Yorkshire.	Nottinghamshire.
Thuringian. — Gypseous marls	Upper red marls with anhydrite and salt, 500 feet.	Upper red marls with stringers of salt, 50 feet.	Absent or represented by pebble beds and sandstones usually regarded as Bunter in age.[2]
Zechstein dolomites	Upper M.L.,[1] 300 feet., and Hartlepool anhydrite	Upper M.L.[1] with anhydrite bands, 50–120 feet.	
		Middle Marls with rock-salt, 30–50 feet.	Middle Marls and sandstones, 20–30 feet.
	Middle M.L.,[1] 150–300 feet.	Middle M.L.[1] with anhydrite and gypsum, 150–200 feet.	
	Lower M.L.,[1] 40–200 feet.	Lower M.L.[1] with anhydrite locally, 120 feet.	Lower M.L.[1] and local sandstone, 60–70 feet.
Kupferschiefer	Marl Slate, 3 feet.	Marl Slate, 5–15 feet.	Marl Slate, 30–50 feet.
	Yellow sands, 0–150 feet.	Quicksands and breccias, 10–20 feet.	Local breccias.

[1] M.L. = Magnesian Limestone.

[2] According to R. L. Sherlock, the Upper Magnesian Limestone and part of the Upper Marls of Durham are homotaxial equivalents of the Lower Bunter of Nottinghamshire.

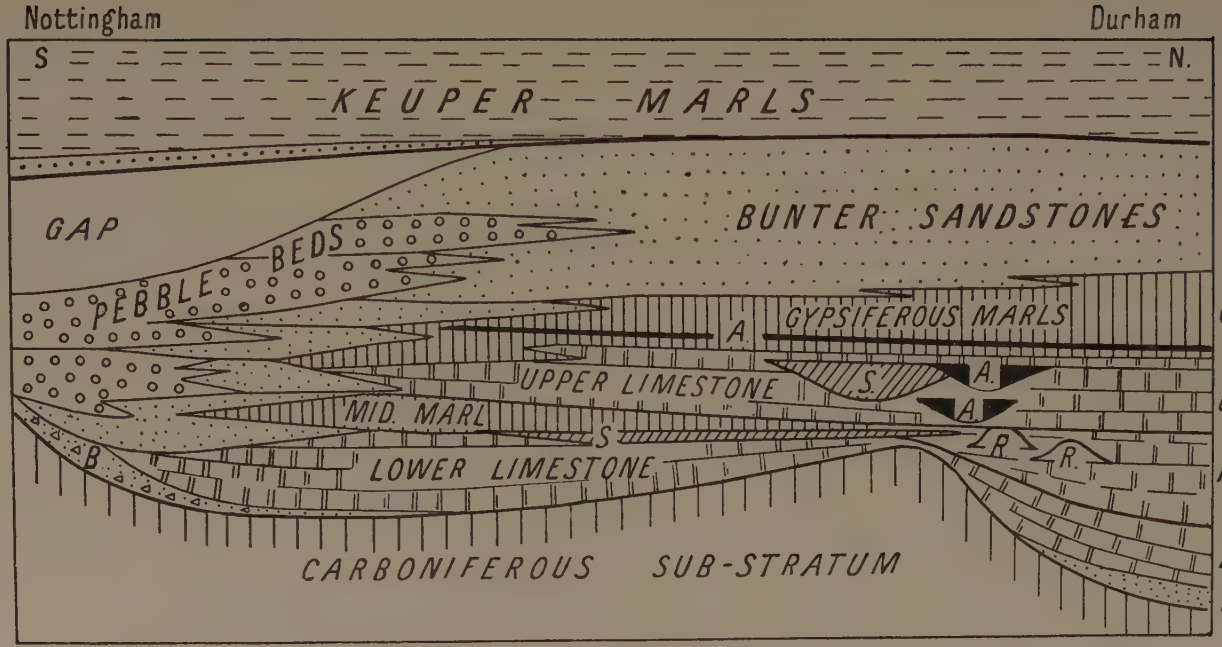


FIG. 39.—Diagram-section from Nottingham to S. Shields, Durham. The lateral variation in the Magnesian Limestone Series and the Trias; largely based on Sherlock.

LL, ML, UL, Lower, Middle, and Upper Magnesian Limestone; B, Basal breccias, sands, and grey beds; A, anhydrite; S, rock salt; R, knoll-reefs. The thickness of the Keuper and Bunter should be greater relative to that of the Permian.

Sherlock the red sands and pebble beds near Nottingham that are usually regarded as Bunter, in reality pass laterally into the "Middle Marl" and "Upper Limestone." He holds that they represent the delta-fan of temporary rivers that entered the sea near here.

The beds of rock-salt and anhydrite in the Upper Marls ("Gypsiferous Marls") indicate a final drying up of the Zechstein waters in a series of salt-lakes, and the subsequent deposition of desert-dust. It is therefore not unnatural to find these strata everywhere succeeded by desert-sandstones and dust-deposits universally regarded as Trias (Bunter and Keuper).

Chemical Precipitation and other Processes in Inland Seas and Salt Lakes.—The proof that the Magnesian Limestone Series with its underlying "Marl Slate" was deposited in an extension of the same sea in which the very similar Zechstein limestone and dolomites and underlying "Kupferscheifer" were laid down in Germany, lies not only in the great similarity of the types of sediment, but in the community of many of the fossils. The latter agree with the other evidence, now to be discussed, in indicating a sea at times connected with the ocean by straits and at other times completely land-locked and exposed to excessive evaporation, as in Lake Timsah and the Bitter Lakes at the head of the Red Sea.[1] Possibly too, even when the connection existed, the straits themselves were shallow, so that only warm surface-currents were admitted from the outer ocean, as is the case in the present Red Sea. In such circumstances, if the climate is hot and if but little river-water enters the sea, evaporation rapidly increases the salinity of the water; but only under exceptional circumstances are the dissolved salts chemically precipitated as long as connection with the open ocean is maintained, for lime-secreting organisms abstract the least soluble salts, viz. calcium carbonate and sulphate. But if concentration of the salts by evaporation proceeds far enough, calcium carbonate is the first salt to be chemically precipitated, either on the sea-floor or around particles of sand or chips of shell. If the latter are rolled about during the process by currents and waves, ooliths (p. 146) are formed. Reefs composed of the hard parts of calcareous organisms reinforced by $CaCO_3$ precipitated in these ways may be readily built up in a highly saline sea, especially in the shallow waters near the shores. The rocks thus formed are often found to be composed, in part at any rate, of the double carbonate of lime and magnesia known as *dolomite*, $CaMg(CO_3)_2$,[2] though the factors

[1] Before their nature was modified by the Suez Canal.

[2] The question arises how far dolomite can be a primary precipitate, and how far it has been secondarily formed by the *metasomatic* process known as *dolomitization*, which involves the addition of magnesium salts to already-formed calcium

controlling the formation of this mineral are not completely known.

Should communication with the ocean be completely severed, the other salts in the water thus cut off may be precipitated from supersaturated solutions caused by an excessive evaporation or by excessive cold.[1]

Experiments seem to show that,[2] after the Calcium- and Magnesium-Carbonates (see above) have separated out, there would follow, first, the anhydrous and hydrous Sulphates of Calcium (Anhydrite, $CaSO_4$ and Gypsum, $CaSO_4.2H_2O$), then Common Salt (NaCl) and Epsom Salts ($MgSO_4$). Finally, as complete desiccation approached, Potassium Chloride (KCl) and other very soluble salts would be precipitated.

We may now examine the deposits of the Magnesium Limestone Series with a view to showing how they agree with the hypothesis of their origin partly in a sea and partly in salt-lakes of progressively increasing salinity, but always lying in hot desert surroundings (Fig. 37).[3]

The basal breccias and æolian "yellow sands" (in Durham) were first deposited as fans and dunes on the surface of the Permian desert, across the nearly level floor of which the sea eventually advanced,

carbonate to form the double carbonate of lime and magnesia, $CaMg(CO_3)_2$. For, though it has long been known that in laboratory experiments dolomite cannot be precipitated directly, yet in nature it appears that it may be formed in salt-lakes from saturated solutions of calcium and magnesium carbonates, perhaps only in the presence of concentrated solutions of other salts. Such an origin is claimed by C. T. Trechmann for much of the dolomite of the Durham Magnesian Limestone (*Q.J.G.S.*, vol. lxx, 1914, pp. 249–59). R. A. Daly also believes that dolomite was in the earlier geological periods precipitated directly from the ocean-waters through the interaction of alkali carbonates derived from the decomposition of organic matter before a complete system of scavenging the sea-floor had been evolved.

The conversion of limestone to dolomite appears to go on under certain physiographical conditions almost simultaneously with the deposition of $CaCO_3$. The change is especially likely to occur in warm saline waters, such as are found along shelving shores and in shallow reef-lagoons in the Tropics. Thus the boring through the modern coral-atoll of Funafuti showed the rock to be largely dolomite, though originally formed of the calcareous hard parts of organisms. Some dolomites, especially those in which traces of fossils occur, may have been built up of calcareous organic debris that has been contemporaneously converted to dolomite, but the absence of fossils in a dolomite cannot be regarded as ruling out such an organic origin.

[1] J. Walther, *Gesitz der Wüstenbildung*, 4th edit., 1924, p. 310.

[2] There is some doubt about this. See J. Usiglio, *Ann. Chem. Phys.*, 3rd Series, vol. xxvii, 1849, pp. 92, 172, quoted by A. W. Grabau, *Principles of Stratigraphy*, p. 348. See also R. H. Rastall, *Physico-chemical Geology*, 1927, p. 180.

[3] P. F. Kendall and H. E. Wroot, *G. of Y.*, pp. 266–72. C. T. Trechmann, *Q.J.G.S.*, vol. lxx, 1914, p. 259.

rapidly flooding it to no great depth. After the dolomitic shale known as "Marl Slate" had been deposited perhaps in fairly fresh-water, as is suggested by the abundant fish, many of them freshwater types, preserved as fossils in it,[1] limestone- and dolomite-formation set in as the salinity increased. The Lower Limestones are in places fossiliferous; so too are the lower members of the Middle Limestones. In Durham Bryozoan barrier-reefs (Fig. 40) (Middle Limestone), at first crowded with life and then progressively more and more barren, fringed the borders of the shrinking sea that by evaporation was becoming more and more saline. This is recorded both by the smaller area covered by the deposits, by the upward passage of fossiliferous strata through sparsely fossiliferous layers into barren beds, and by the progressive dwindling in the number of the fossils and by their gradual dwarfing and distortion.[2] These are mainly molluscs and Bryozoa[3] (*Fenestella*, *Syncladia*, *Thamniscus*), and the dolomites and limestones in which they occur must have originated in the same way as the Bryozoan reefs that fringe the Red Sea to-day. Trechmann, speaking of the Durham reef, says it "affords a curious example of a fauna apparently caught and locked in a sea, and gradually exterminated as the conditions of life became less favourable." In Durham the fringing reefs, or perhaps more correctly barrier-reefs, ran more or less from north to south (Fig. 40). On their seaward or eastern flank the reef-limestones in places pass into breccias, the components of which are, it is believed, blocks of limestone torn by the waves from the reef, and deposited on its outer slopes as "*reef-talus*" (see p. 316).

In Thuringia the southern shore of the same sea was fringed by exactly similar reefs.

Reverting to the lithological characters, the "Lower Limestones" are mainly dolomites from Nottingham to Durham. The oolitic structures (p. 146) that they display and the shallow-water nature of their contained fossils, point to a sea of no great depth. We have shown already that the Middle Limestones of Durham are partly organic reef-deposits and partly chemical precipitates. Their equivalents southwards, however, are salt-, gypsum-, and anhydrite-bearing red marls (Fig. 39). These characters indicate that in the south the sea had retreated, leaving South Yorkshire and Nottinghamshire in the state of salt marshes or salinas in which the salts rapidly became highly concentrated by evaporation until finally many of them were precipitated from supersaturated solu-

[1] J. Walther, *op. cit.*, 1924, p. 364.

[2] C. T. Trechmann, *Proc. Geol. Assoc.*, 1925, vol. xxxvi, pp. 143–5.

[3] Bryozoa are small marine animals whose calcareous skeletons largely build up the reefs.

tions. The marls themselves probably represent wind-blown dust that was arrested by the surface dampness caused by the hygroscopic nature of the salt-impregnated mud. According to Sherlock, still farther south delta-fan conditions marked the edge of the cuvette, and are recorded by the Nottinghamshire Pebble Beds (Fig. 39) (usually regarded as Trias). These Middle Marls with their deposits of chemical precipitates represent a stage in which the waters had shrunk to a number of separate sheets over Yorkshire, though a more definite sea still persisted in the north and probably in the east. It is natural, therefore, to find the deposits distributed somewhat sporadically. The water in these lakes must normally have been very hot, for anhydrite is the commoner form of calcium sulphate in the deposits. This mineral is only precipitated from saturated solutions of common salt at temperatures above about 97° F. (36° C.),[1] but in the presence of other salts it might perhaps separate at somewhat lower temperatures. Below the critical temperature (round about 85–100° F.) the hydrous form of calcium sulphate (gypsum) is thrown down. Anhydrite therefore, if primary,[2] provides a sort of geological thermometer that indicates temperatures far in excess of the mean temperature of the hottest parts of the ocean to-day, that of the Red Sea being 73° F. and that of the Persian Gulf 75° F., and it is likely that the temperatures required are only to be found

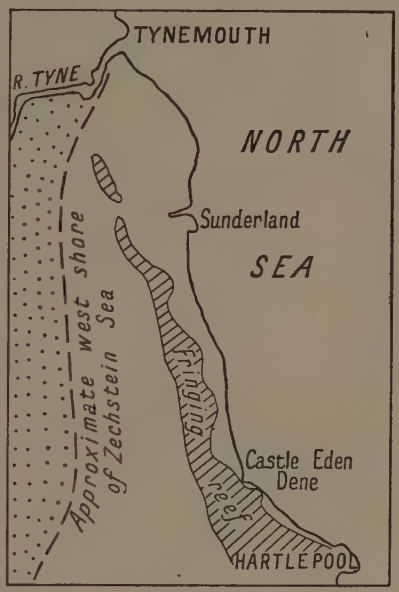


FIG. 40.—The Fringing- or, better, Barrier-reef of "Shell-limestone" (diagonal ruling) bordering the western shore of the Zechstein Sea in Durham (Middle Magnesian Limestone).

Land stippled. Based on C. T. Trechmann.

[1] R. C. Wallace, *Geol. Mag.*, 1914, pp. 271–6. B. Smith, *Q.J.G.S.*, vol. lxxiv, 1918, p. 195. P. F. Kendall and W. E. Wroot, *Geol. of Yorkshire*, p. 269. R. H. Rastall, *Physico-chemical Geol.*, 1927, p. 181.

[2] In Germany in similar beds it is usually regarded as secondary, and produced by the dehydration of gypsum when the rocks have been subjected to high temperatures owing to having been deeply covered by other strata.

in enclosed bodies of shallow water. Thus the anhydrite of the Magnesian Limestone Series conjures up a picture of salt-lakes, salinas, and salt-pans, the waters in which were steaming under a grilling tropical sun.

According to Prof. Kendall's interpretation, communication with the ocean was reopened after the "Middle Marls" had been laid down, and fresher waters were admitted in which the fossiliferous lower part of the Upper Limestones were deposited in Yorkshire. But the sea became cut off again, and grew rapidly more and more saline, as is particularly clearly indicated in Durham by the dolomitic and oolitic nature of the limestones, by the original intermingling of chemically precipitated dolomite with anhydrite or gypsum, and by the presence at Hartlepool of a thick mass of anhydrite (265 feet thick) which in part shows horizontal interbedding with layers of dolomite.[1] The close association of dolomite and anhydrite supports the idea that the dolomite was in this case a primary precipitate [2] from very saline water, perhaps of peculiar composition, and all the features agree with the hypothesis of progressive evaporation of the salt water and the diminishing of the area of the sea.

Finally, the "Upper Limestones" are followed by the red Upper or Saliferous Marls with anhydrite, gypsum and rock-salt (the last especially near Middlesbrough). This records a repetition of the salt-marsh or salina environment that had occurred before in the "Middle Marls." The salinas probably dwindled gradually from south to north; for the marls are thinner in the south, and therefore the salt-marsh condition ended earlier there. Everywhere the Upper Marls are followed by sands and gravels of delta-fan origin, that are classed as Bunter. The North-Eastern Cuvette had now become a desert-basin without permanent bodies of standing water; and into it inconstant torrents and wind-storms carried gravel, sand and dust. These conditions are further discussed in the next chapter.

In Germany, the Upper Permian strata tell a similar story of arid conditions. The dolomites of the Zechstein are followed by clays containing immense deposits of chemical precipitates, including especially anhydrite, gypsum, rock-salt, and at Stassfurt the potash-salts that make Germany the chief producer of potassium in the

[1] Compare the alternations of rock-salt and anhydrite at Stassfurst discussed on p. 103.

[2] Trechmann is inclined to regard the majority of the Magnesian Limestone dolomites as primary precipitates, though prepared to admit that dolomitization may have taken place at the time of formation of the limestone. There has, of course, been secondary dolomitization as well (see note, p. 98).

world. The Stassfurt deposits are some 200 metres thick,[1] and include about thirty different minerals, of which anhydrite and rock-salt form the greater bulk, while the various sulphates and chlorides of magnesium and potassium have the greater interest and value.

The presence of potash-salts in the upper part of the deposits implies by reason of their great solubility the complete desiccation of a salt-lake. For the same reason they must have been very effectively sealed up by impervious marls, which it seems likely originated as desert-dust, arrested by a slight surface-dampness inevitable with such hygroscopic salts.

A great part of the Stassfurt deposits consists of alternating layers of rock-salt and anhydrite. This character is supposed to record the annual variation in the salinity, such as might result from a seasonal rainfall followed by drought. After the rains, the lake-water was too fresh for the precipitation of rock-salt, and yet concentrated enough for anhydrite to separate out; but as the drought proceeded, rock-salt might be thrown down from a supersaturated solution. A second explanation has also been put forward,[2] namely that the sulphates being less soluble in hot water were precipitated in summer; whereas rock-salt, being less soluble in cold water, was thrown down in winter. Such alternations of wet and dry, or hot and cold seasons are usually annual; and on this supposition, it has been calculated that the deposits exhibiting these alternate layers represent a period of some 10,000 years.[3]

The local nature and special conditions governing the formation of deposits like the Stassfurt salts may be well illustrated by the present-day conditions on the coast of Eretreia[4] on the south side of the Red Sea. Here is a depression that was once part of the sea, but which has been separated from it by a belt of volcanic rocks. Under the grilling tropical sun the sea-water has evaporated, leaving a plain of salt, near the centre of which two types of potash-deposits

[1] Vast volumes of sea-water would be required to provide all this salt. Ochsenius has suggested that the water in the inland sea was periodically renewed by ocean sea-water that reached it over a sand-bar. Walther, on the other hand, repudiates this view, and regards the deposits as the accumulation of salts derived from the surrounding desert-wastes, and washed into a basin by seasonal rainfall after the manner of the great Persian salt-marshes or salt-lakes known as Kavirs and first investigated by Sven Hedin (see J. Walther, *op. cit.*, pp. 304 and 366).

[2] W. Köppen and A. Wegener, *Die Klimate der Geol. Vorzeit*, 1924, p. 41.

[3] For full discussion of salt-deposits, see A. W. Grabau, *op. cit.*, pp. 347–80, also references. For factors governing salinity and the formation of salt-deposits in arid regions, see J. Walther, *op. cit.*, pp. 297–314.

[4] A. Holmes, *Geol. Mag.*, 1919, p. 340.

are found: Carnallite, an impure form of potassium chloride, with 15 to 25 per cent KCl, covers an area of 2 million square yards, and is as much as 159 feet thick, while Sylvite, which is almost pure KCl, occurs over a much smaller space and to a depth of 2 to 5 feet.

CHAPTER IX

THE TRIASSIC SYSTEM

The Nature of the Triassic Record.—The general geographical conditions in Europe during Triassic times were not very dissimilar to those of the Permian. The dominant features were the geosynclinal sea of Tethys in the south, and an arid or semi-arid continental region stretching northwards from Southern Bavaria to Scotland and probably far beyond. Part of this continent was flooded by the sea during the middle of the period (Muschelkalk Sea) (Fig. 41).

Tethys has already been referred to as existing in Permian times, and it will be seen later that it persisted throughout Mesozoic and early Cainozoic times as a rather narrow geosynclinal sea trending roughly along the line of the Alps, Balkans, Caucasus and Himalayas, which mountains have all been mainly constructed from the sediments, partly neritic, but mostly bathyal, thrown down on its floor.[1] This so-called "Alpine" development of the Mesozoic and Lower Cainozoic systems is characterized by great thicknesses of rock, generally in unbroken sequences, and by a distinctive assemblage of fossils, many of which are unknown in the contemporary deposits of Western and Central Europe.

The English and German facies, known as the "Continental" or "Germanic" Trias is most fully developed in Southern Germany, where it can be divided into three stages, and it is from this fact that the term Trias (Threefold) is given to the system. The groups are:

Keuper—Continental sediments, mainly marls.

Muschelkalk—Epicontinental marine limestones and dolomites.

Bunter—Continental sediments, mainly sandstones.

In Bunter times Europe north of the present Alps [2] was more or less a desert with scree-covered mountains and intermont plains whose sand dunes and torrent-fed delta-fans were mingled here and

[1] In it flourished in Triassic times creatures which were at once the descendants of the Carboniferous and Permian, and the forerunners of the Jurassic marine faunas. This is especially the case in the Ammonites (p. 62).

[2] For a general account of the German development, see E. Fraas, "Bildung der germanischen Trias," *Jahresh. d. ver. f. vaterl. Naturk. in Württenberg*, 1899; J. Walther, *Geol. Heimatkunde von Thüringen*, 1901, and *Gesitz. d. Wüstenbilding*, pp. 367–9; E. Hennig, *Geol. v. Württemberg*, Berlin, 1923, chap. iv.

there with salt-lakes and playas or salt-pans. The principal deposits were laid down in cuvettes in Germany and England (Fig. 43*a*).

During Middle Triassic times (Fig. 41) there was an incursion of the waters of Tethys into the German Cuvette resulting in a shallow land-locked gulf that extended over Germany into Eastern France and northwards as far as Heligoland. In it was deposited the shelly limestones and dolomites of the Muschelkalk, which contain a few marine fossils, some of which are also found in beds laid down in Tethys. By means of these fossils a correlation is possible between the two very different facies of the Trias.

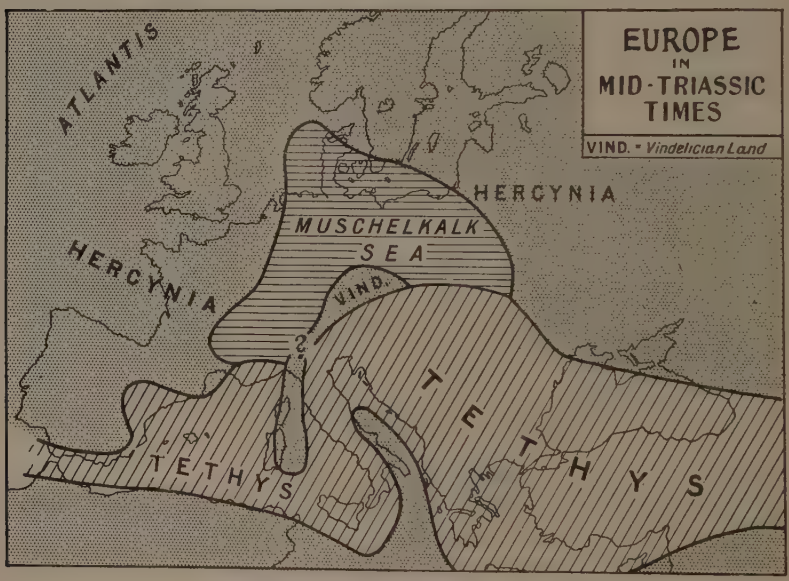


FIG. 41.—Europe in Mid-Triassic times.
Land stippled.

The Keuper deposits were in part sandstones, but mostly marls and gypsum. They indicate a return to continental conditions and a general reduction in the relief of the country whereby the source of supply of coarse detritus was much restricted, while the area where sedimentation could go on was greatly enlarged (p. 108), and eventually covered much of France and England as well as Germany (Fig. 43*b*).

British Trias.

In later paragraphs it will be shown that the nature of the rocks and of the fossils in the British Trias indicate a continuation of the

Permian continental environment during their formation. The region was still merely a part of the Hercynian continent and lay as before in a semi-arid and probably tropical belt. Of the cuvettes where Permian deposition had taken place, those on both sides of the Pennine Chain and in Devon persisted as sites of practically continuous sedimentation into and through Triassic times. This is so much so that it is extremely difficult, as has been already pointed out, to define the limits of the two systems. But all across the Midlands uplift and denudation had taken place in the interval between the formation of the so-called Permian and of the Triassic rocks, and consequently the two systems are here defined by means of the unconformity between them (p. 79).

The Triassic rocks at the present day floor a central area in Shropshire, Worcestershire, Warwickshire, Staffordshire, and Leicestershire, that is continued by three arms: one runs through Cheshire and Lancashire to subsidiary areas of outcrop in the Isle of Man, the Lake District, Antrim and South Scotland; the second passes northwards on the east side of the Pennines; while the third spreads into Gloucestershire and South Wales and thus, by discontinuous outcrops, connects with another important Triassic area in Somerset and Devon (Figs. 32 and 43).

The Trias may be divided as follows in the Midland Cuvette, which is chosen as affording the fullest sequence:

Keuper	Keuper Marls	Red and mottled marls with thin sandstone bands and beds of rock-salt, gypsum, anhydrite, and celestine.
	Keuper Sandstone	Red and buff sandstones with some breccias and conglomerates.
Bunter	Upper Mottled Sandstone	Red and grey sandstones.
	Pebble Beds	Sandstones with lenses of coarse gravel.
	Lower Mottled Sandstones	False-bedded red and grey sandstones.

These subdivisions cannot be recognized with certainty either in north-east or north-west England or in Devonshire. It will be noted that no reference is made to the Muschelkalk. The waters of the Muschelkalk Sea never reached into Britain, and it is probable that during the time of its formation only continental deposits were being laid down here. In the absence of fossil evidence it is impossible to say which part of either the British Bunter or Keuper or of both is the homotaxial equivalent (p. 62) of the Muschelkalk Limestone.

The Overlap of the Higher Beds.—The sequence given above is complete in Lancashire, Cheshire, and North Shropshire; but elsewhere a variable amount is missing from the lower parts, and the individual formations are thinner. If we could restore the original arrangement before any earth-movement had taken place, it would be found that in passing east and south-east from Lancashire, the formations thin out and disappear one after another, beginning at the base (see Fig. 42). This implies that the deepest part of the cuvette and that in which sediment first began to accumulate in Lower Bunter times, lay over what is now Lancashire, Cheshire and Shropshire; and that the area where accumulation could take place, small in Lower Mottled Sandstone times, gradually increased as the basin became filled up (Figs. 43 *a* and *b*). In this way we can account for the thinning out of the lower beds, and the much wider distribution of the upper ones. Each bed, in fact, when traced away from the centre of the basin *overlaps* the one below it and comes to rest on a surface consisting of far older rocks. The lowest member of the formation in different areas may therefore be of very different ages. The sub-Triassic unconformity for these reasons forms a striking example of the second type of unconformity described on p. 65; and as such will be examined in detail (Fig. 47).

The irregular basin in which the Triassic rocks were laid down was due partly to tectonic causes and partly to erosion. Not only do we know its general shape, but in several places the hills and valleys of that ancient buried

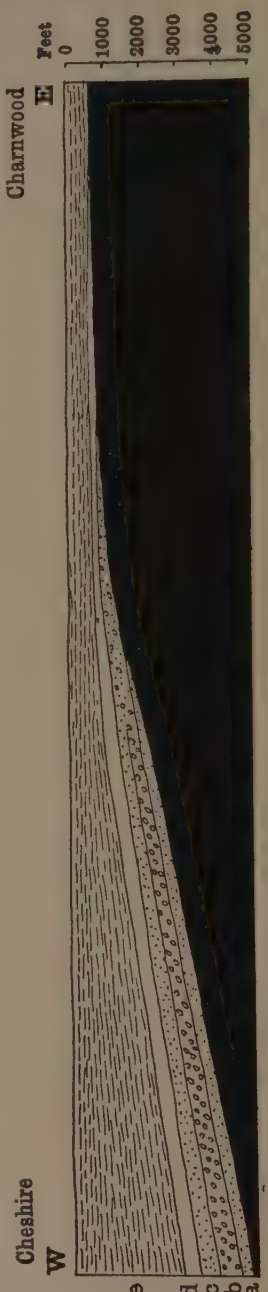


FIG. 42.—Overlap of higher over lower Trias. After Lake and Rastall.

landscape can still be seen. The best known examples are found in Leicestershire [1] and in the South Wales and Bristol Coal-fields, and in all these cases the old surface is buried under deposits of Keuper age; but the Bunter plays the same rôle in Nottingham-shire.

In Leicestershire, in addition to natural exposures, extensive quarries exploiting for road-metal the ancient igneous rocks of

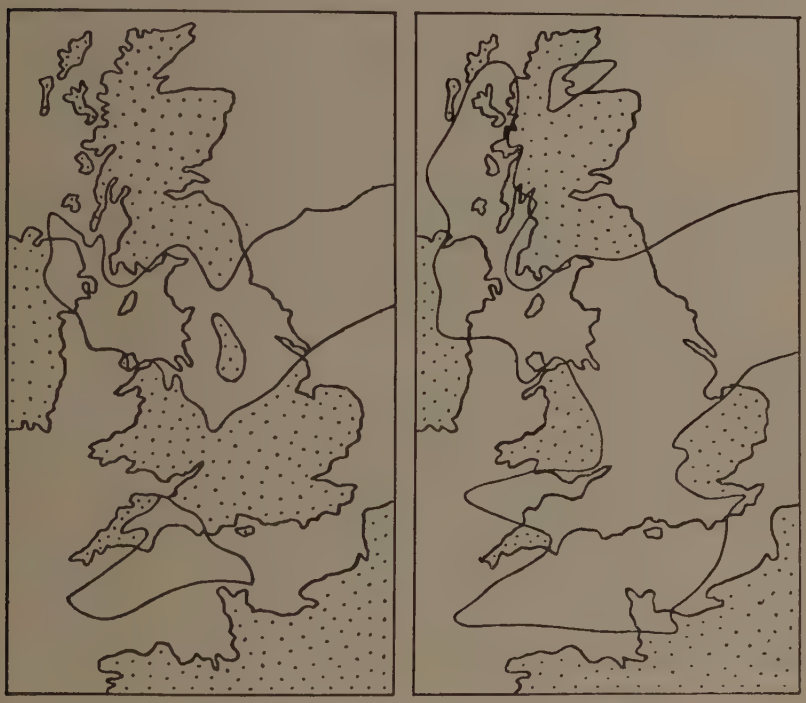


FIG. 43.—(*a*) Bunter geography. (*b*) Keuper geography.
(Areas of Deposition unstippled. (After Jukes-Browne.)

Charnwood and south Leicestershire, have revealed in a striking manner the nature of the surface that was covered by the Keuper Marls (p. 120). Valleys and hills can be seen buried beneath the

[1] W. W. Watts, "Charnwood Forest, a buried Triassic Landscape," *Geogr. Journal*, 1903. T. O. Bosworth, "The Keuper Marls around Charnwood," *Leicester Lit. and Phil. Soc.*, Thornley & Son, Leicester; and *Q.J.G.S.*, vol. lxviii, 1912, p. 281.

marls [1] and, in some cases, beneath their own scree that now forms a basal breccia to the Keuper (Fig. 44).

The shape of the ancient valleys varied with the type of rock through which they happened to pass, as did also the smaller features of the surface. The fine-grained South Leicestershire Syenite has been carved into "lumpy fretted slopes, U-shaped gullies and convex bumps devoid of points or edges, and the surface of the stone is pitted and sometimes highly polished." The granite of Mount Sorrel, on the other hand, gives smoother slopes that are

FIG. 44.—Steep Rock-slope and Scree below Keuper Marl, Croft Quarry.
B, Breccia; K.M., Marl; both dipping steeply away from the Triassic hillside of S, Syenite. (From a photo by T. O. Bosworth.)

grooved and terraced. In some places the terraces are undercut and probably owe their shape to the corrasive action of the wind (Fig. 45). Elsewhere, cleaved rocks have been carved into V-shaped gullies, crags, and angular ragged surfaces.

The Charnian rocks below the sub-Triassic floor are quite fresh, in sharp contrast to their deeply weathered condition when they form the present surface. The freshness indicates that the Triassic

[1] The marls are nearly horizontal as a rule, but where they lie over the site of a Pre-Triassic valley they dip towards the bottom of the valley. This feature is due to the contraction of the marls during drying and consolidation (see p. 55).

climate was markedly different from the present moist one, and is in accord with the view that the sediments accumulated under arid conditions in which the mechanical breaking-up of the rock predominated. The unweathered sub-Triassic rocks shown in Figs. 44 and 45 should be compared with the present-day weathering illustrated in Fig. 11, p. 25.

The sub-Triassic surface in South Wales,[1] near Bristol, and in Somerset is somewhat similar to that of Charnwood Forest and Leicestershire. A peculiar rock of the breccia-type is found here

FIG. 45.—Wind-cut cliffs of Granite (G), still partly concealed by adherent Keuper Marl (KM).

Note undercutting, and fretted upper surface of the granite with knobs protruding through the Marls. Mount Sorrel, Leicestershire. (From a photo by T. O. Bosworth.)

at the base of the Keuper Marls. It is known as the "Dolomitic Conglomerate," since it consists locally of blocks of limestone cemented by a dolomitic matrix. This rock-type occurs wherever the Triassic surface had consisted of the Carboniferous Limestone. Sometimes the breccia merges into inorganic limestones that represent the smaller, possibly wave-washed, debris of the limestone. Where, however, the Triassic surface had been composed of the Old Red Sandstone, the fragments in the basal Triassic breccias are no longer limestones, but sandstones, and the rock presents a very different appearance.

[1] A. H. Cox, *P.G.A.*, 1920, pp. 69–73. A. Strahan, "Country around Bridgend," *Mem. Geol. Surv.*, 1904, and *Geol. in the Field*, p. 842.

The distribution of the deposit shows it to have originated in valleys and hollows of the hills bordering the cuvette, and around isolated eminences like the Quantocks and Mendips which stood

FIG. 46.—"Islands in the Keuper Lake."
Land in Keuper times shaded. (Adapted from Lloyd Morgan.)

up above the plain on which the Keuper Marls (p. 120) were forming, perhaps at times as islands in a salt-lake, perhaps at other times as "inselbergs" or "kopjes" [1] (Fig. 46). This landscape

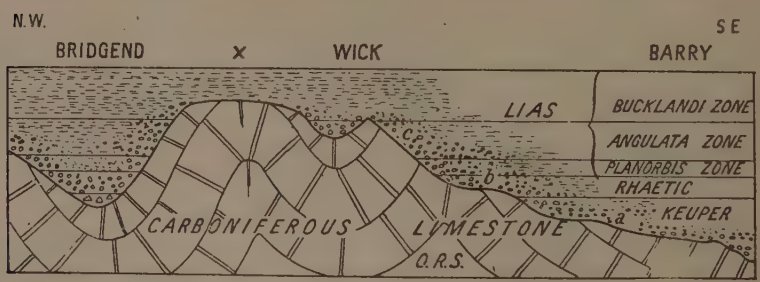


FIG. 47.—Diagram showing the Unconformable Relation of the Mesozoic to the Palæozoic Rocks in Glamorgan. Unconformity of Type 2.
Horizontal lines, zones or time-limits; littoral facies stippled; apparent conformity at X. (Adapted from A. E. Trueman.)

gradually sank below the accumulating sediments, the breccias continuing to be built up around the prominences, while marls

[1] Lloyd Morgan and S. H. Reynolds, *Proc. Bristol Nat. Hist. Soc.*, 4th Ser., vol. ii, 1909, p. 5.

formed farther away. Hence various parts of the breccia formation are of very different ages (Fig. 47). Further, the bands of breccia pass into marls when traced laterally away from the old hills from which they were derived. As in the Permian Breccias the angular nature of the fragments shows that they originated as talus formed under hot, arid or semi-arid climatic conditions.

The Continental Origin of the Deposits.—The dominant rock-types of the Triassic formation will now be examined in order to see what evidence they present of the continuation of the continental and semi-arid conditions of the Permian.[1]

All the rocks, alike breccias, pebble-beds, sandstones, and marls, are as in the Upper Coal Measures and Permian predominantly red or red-brown in colour. The significance of this in relation to a desert origin has already been discussed (p. 85). For the same reason no further reference will be made to the breccias, except to state that they usually occur near what was, at the time of their formation, the limit of the region of sedimentation.

As already pointed out, the Bunter consists of coarse bright-red sandstones and pebble beds or conglomerates, whereas the Keuper is essentially a marl formation; though fine, often brown or grey, rather than red, sandstones occur in its lower part.[2] The conditions governing rock-accumulation were therefore clearly somewhat different in the two periods.

The Bunter Sandstones and Pebble Beds.—In the Bunter,[3] it is convenient to examine the characteristics first of the sandstones and then of the pebble beds, though it is difficult to treat them separately on account of the intimate interdigitation of the two types.

Sandstones.—The sandstones are usually friable and barely cemented, and of a bright red colour that is due to each grain being coated with hematite. Sometimes there are red or green marls associated with them, whence comes the name "mottled sandstone."

The sand grains are mostly quartz, usually fairly well-rounded. Some beds, known as "Millet-seed Sands," consist of very uniformly graded, rather large, well-rounded grains, characteristics that are typical of æolian sands, though it must be recalled that it is possible for water to round such large grains as compose this variety. Daubrée, Mackie, Scherzer[4] and others have, however, pointed out

[1] In addition to the references already given, see J. Lomas, "Desert Conditions and the Origin of the British Trias," *Proc. Liverpool Geol. Soc.*, 1906–7, p. 172.

[2] See also p. 118.

[3] German "Bunter" brightly coloured or variegated.

[4] A. Daubrée, *Études synthetiques de géologie expérimentale*, Paris, 1879. W. Mackie, *Trans. Edinburgh Geol. Soc.*, vol. vii, 1897, pp. 298–311. W. H. Scherzer, *Bull. Geol. Soc. America*, vol. xxi, 1910, p. 633. V. Zeigler, *Journal of Geol.*, vol. xix, 1911, pp. 645–54.

that wind is the only agent capable of rounding grains less than about 1·0 to 0·75 mm. diameter. For this reason the presence of fine-grained, well-rounded sands in the Bunter is really as strong a piece of evidence in favour of an æolian origin as the "Millet-seed Sands." On the other hand, the extremely uniform size of the grains in the latter variety can hardly be due to anything but the wind; for a far more accurate grading, according to the size and density of the grains, is effected by air- than by water-currents. Yet neither rounding nor grading is necessarily conclusive evidence that the rock was deposited on land, for the wind may blow rounded and graded sands into the water of sea or lake.

Some of the sandstones contain pellets of hardened clay, comparable with those in the Carboniferous pellet-rocks (see p. 86). As in that case, so here flakes of sun-baked mud from the bottoms of dried-up playas were blown by the wind or rolled down by a flood, to be incorporated as pebbles in strata of practically the same age. As no earth-movement had affected the clay, this phenomenon is an example of "contemporaneous erosion" in contradistinction to "interformational erosion" by which pebbles are carved from uplifted and consolidated rocks, and are ultimately brought together as gravels or shingle to form conglomerates in a far newer series. Occasionally one can see the clay-pellets in a Triassic sandstone associated with a discontinuous band of marl from which perhaps they may have been derived. The pellet-rocks are usually found in sandstones, the irregular bedding of which is equally suggestive of deposition from, and partial erosion by shifting streams traversing a delta-fan.

The Bunter sandstones of the West Midlands and Lancashire show little sign of true parallel bedding, but consist of a "tumbled series of eroded lenticles." Those in the Lower Mottled Sandstone of Bridgnorth display on a large scale the type of false-bedding known as "diagonal bedding," individual lenses of sand being sometimes 20 feet thick (Fig. 48). These very probably originated as sand dunes; though little is known at present about the diagnosis of conditions of deposition from the type of false-bedding. The subject offers a good field for research.[1]

Pebble Beds.—Pebble beds or conglomerates occur at two chief horizons in the British Trias, namely in the Bunter and at the base of the Keuper. The former are commonly known as the Bunter Pebble Beds; and, as developed in the Midlands, they consist of coarse red sandstones with thick or thin seams of uncemented gravel of very well-rounded hard pebbles. Traced laterally, the beds of gravel give place to sandstones with or without scattered pebbles;

[1] A. W. Grabau, *Principles of Stratigraphy*, pp. 701–6.

but, distributed as they are across the Midlands from near Birmingham to Lancashire and South Yorkshire, they cover too great a spread to be considered as a beach-deposit. They are now generally accepted as river-borne material laid down in a delta.

The pebbles are usually of quartz or of quartzite, with an admixture of other hard rocks. The size varies from $\frac{1}{4}$ inch up to 4 or 5 inches; though round Birmingham stones 8 or 9 inches across are common and occasional partially-rounded blocks reach a diameter of 2 feet or more. Some of the pebbles are covered with minute circular cracks or chatter-marks [1] that bear witness to the pounding

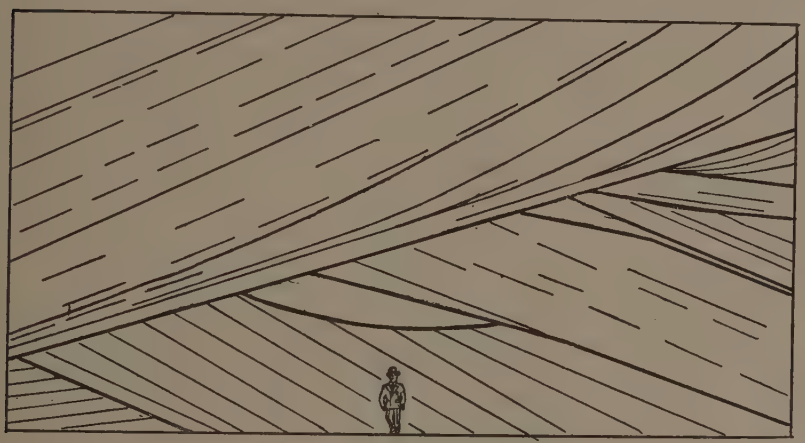


FIG. 48.—False-bedding in the Lower Mottled Sandstone (Bunter); Lower Forge, Eardington, Bridgnorth. Height of section, 40 feet. (From a photo.)

to which they had been subjected in their river-journey, and which had destroyed the less tough varieties, save where exceptionally a soft stone of quite local derivation is present. In the gravels themselves there is often very little sign of stratification or false bedding, and the pebbles lie without any definite orientation of their longer axes. Sand occurs as lenses rather than in the interstices between the pebbles. These features are not characteristics of normal delta-gravels formed in permanent bodies of water [2] (Fig. 50), but are what might be expected to occur in gravels originating at times of flood on desert delta-fans, the gravels being modified during the dry

[1] Not to be confused with the pittings so often to be seen on the pebbles. The pittings are due to the gradual grinding of one pebble into another, that has been effected by repeated earth tremors acting during prolonged periods on the uncemented gravels.

[2] The characteristic bedding of torrential delta-deposits is dealt with on p. 118.

seasons through the removal of the sand by wind, with the resultant concentration and rearrangement of the stones.

The Pebble Bed Formation is therefore best regarded as the delta of a large river or rivers which, fed by the heavy, probably seasonal, rainfall in distant mountains emptied themselves into the Midland Cuvette, much in the way that the Helmand [1] River in spring floods the desert-plains round Lake Seistan or that the Amu-Darya (the ancient Oxus) "sweeps down upon the Turkestan lowland desert," with its inland Caspian and Aral Seas. The size and perfect rounding of the stones betokens a long journey in swift currents.[2] Occasionally, proof of the arid conditions prevailing on the delta is forthcoming, as, for example, near Nottingham where a wind-swept surface has been preserved with pebbles lying on it that have been carved by the wind into dreikanter (see p. 29).[3]

Prof. Kendall [4] points out how the Oxus has altered its course, sometimes flowing to the Caspian and sometimes to the Sea of Aral, shifting its channel on its own delta-fan. "So it spreads over the steppes the debris from the heights, marking its course with bare patches of sand open to wind-action, with salt-pans, gravelly wastes, fertile oases and reed-brakes. Such precisely is the picture we would draw of the early Triassic landscape in England."

The nature of the sandstones of the Bunter accord well with such a picture which allows for the formation of some of them as sand dunes, and of others as the finer sediments of the delta-fans or of the temporary sheets of flood-water.

The evidence of the fossils agrees also with this view, for the only aquatic creatures preserved in these practically unfossiliferous strata are the little bivalve crustaceans, *Estheria*, whose nearest living relatives appear in myriads at the present time, as soon as the rains fill up the "vleys" or wet-season pools on the South African Veldt. Their shells are rare in the Bunter, but relatively common in the Keuper.

The Drainage Basins of the Bunter Period.—The source from which the pebbles in the Bunter Pebble Beds were derived and accordingly the direction from which the rivers flowed, is not definitely known; and a discussion of the evidence and theories would lead us beyond the scope of this book. Prof. Bonney advocated a northerly origin, while others argue for rivers entering the cuvette from the south or south-east.[5] The fluviatile and deltaic origin is, however,

[1] G. B. Tate, *The Frontiers of Baluchistan*, 1909.

[2] Some of the pebbles may have been derived ready-made from older conglomerates.

[3] H. H. Swinnerton, *Geol. Mag.*, 1914, p. 208.

[4] P. F. Kendall and H. E. Wroot, *G. of Y.*, p. 290.

[5] T. G. Bonney, *Q.J.G.S.*, vol. lvi, 1900, pp. 287–303. A. J. Jukes-Browne, *Building of the British Isles*, 4th edit., 1922, pp. 232–6.

generally accepted. If Prof. Kendall's comparison with the Oxus be valid, the possibility that the Triassic river changed its course on its own delta-fan, helps us to overcome one of the objections urged against a southern origin, namely the bifurcation of the deposit northwards from the Midlands to either side of the Pennine Chain.

In Devon and Somerset, similar conglomerates are again found in the Bunter. Here it is possible to come to some conclusions from the evidence contained in the deposits themselves, as to the directions

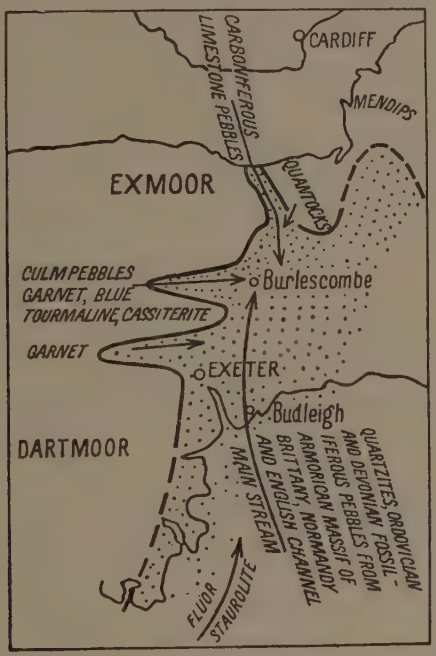


FIG. 49.—The South-Western Bunter Cuvette.

Area of deposition stippled. (Based on E. C. Martin, H. H. Thomas, and D. Stamp.)

from which the rivers drained, and as to the margins of the area of deposition. Dartmoor, Exmoor, the Quantocks, and the Mendips formed the margin of the cuvette which may at times have held a lake (Fig. 49). The pebbles at Budleigh Salterton in Dorset consist of rock-types derivable from Normandy, whereas between Exmoor and the Quantocks pebbles of Carboniferous Limestone seem to have been introduced from South Wales. Between these two areas lies a district round Burlescombe, where the pebbles were derived from the west. A study of the heavy minerals occurring in the associated sandstones confirms the threefold source of the material, which is

suggested by the distribution of the rock-types found as pebbles in the conglomerates.[1]

The Keuper Sandstones.—In the Keuper period, it appears that the planation of the continent was becoming more complete, partly by erosion of the heights and partly through the filling up of the depressions with sediment. This is true not only for Britain but for Germany; for the sandstones of the Lower Keuper are in both areas less coarse as a rule than those of the Bunter, and are followed upwards by a far-stretching series of red and mottled marls in which occur beds of rock-salt and gypsum.

The Lower Keuper Sandstone of the Midlands and corresponding sandstones in Germany are characterized by a grey or brown-red colour, by intercalations of marl, and by the presence of fossils. We may briefly consider the British types. The quartz-grains are here often angular, rather than rounded, and at some horizons are mixed with a fair proportion of very fresh felspar-fragments, sometimes up to half an inch in length. The significance of the unweathered state of the felspar as denoting the breaking up of felspar-bearing rocks by desert weathering has already been referred to (p. 88). Other sandstones contain marl-pellets (p. 114).

Although the material may have been weathered in an arid climate, there is abundant evidence that much of the Keuper Sandstone was water-laid. Often the rock is pebbly and exhibits false-bedding of a type produced by a flooded torrent where it throws down a delta in standing water. At the outer edge of the delta the pebbles and sand roll down and come to rest on the steep slope that drops away to the deep still water; and accordingly in section the bedding is inclined to the general lie of the deposit at a considerable angle, the amount depending chiefly on the coarseness of the sediments. This part of the deposit is known as a fore-set bed (see Fig. 50). As the flood subsides and also as the delta grows gradually out into the lake, the fore-set bed is covered with a horizontal top-set bed, usually of finer material. Should the level of the water rise, the process may be repeated. This type of false-bedding is usually known as current-bedding, and is often observed in the Keuper Sandstones. Occasionally a second type of false-bedding is found, in which the beds have irregular curved surfaces; but it is not known for certain under what conditions this structure is produced.[2]

At Bromsgrove in Worcestershire this type of bedding occurs in sandstones that are often full of marl-pellets and sometimes contain fragments of the bones and teeth of Amphibians and reptiles. It is

[1] H. H. Thomas, *Q.J.G.S.*, vol. lvii, 1902, p. 620. E. C. Martin, *Geol. Mag.*, vol. xlvi, 1909, p. 150.

[2] L. J. Wills, *P.G.A.*, vol. xxi, 1910, pp. 259–62.

likely that both fossils and marl-pellets were the debris gathered by floods from a desert-surface; but amongst the sandstones are lenses of well-bedded, evidently water-laid marl in which remains of fish, plants, and scorpions have been found. *Estheria* (p. 116) is also common. The lenses are often only a few score yards across, and were clearly laid down in small pools or backwaters. It seems likely, therefore, that this part of the Keuper Sandstone formation originated as a delta of a more or less permanent river that traversed a desert. As is the case with the Nile, so perhaps here, vegetation was limited to the flood-plain and delta.

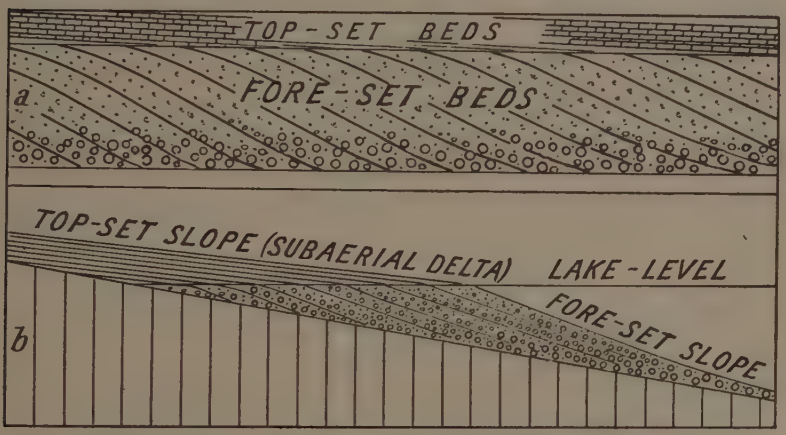


FIG. 50.—Diagram to show (*a*) a coarse conglomerate passing upwards first into current-bedded sand and then into horizontally-bedded sand; and (*b*) the method of their formation as a delta deposit. (Vertical scale exaggerated.)

The continuous lines in the delta bound contemporary deposits.

There are not many fossils known from the Keuper Sandstones, but they throw some light on the environment. Numbers of small fish are occasionally found, that appear to have met their death under circumstances that reflect the semi-arid surroundings. Writing of a shoal unearthed near Nottingham, Swinnerton states: "In the case of the slabs with undulating surfaces numerous well-preserved remains of *Semionotus* were found embedded side by side in the rock, at a depth of from one-eighth to a quarter of an inch below the surface [of the slab]. This mode of occurrence was strongly suggestive of the habit exhibited by some existing freshwater fishes. In dry seasons, when there is a danger of the water drying up, they bury themselves in shoals in the mud at the bottom of the canal or pool in which they live, and remain there until the water is renewed. For the particular fossil fishes under discussion this renewal evidently came too late."[1]

[1] H. H. Swinnerton, *Q.J.G.S.*, vol. lxxxi, 1925, p. 87.

The semi-arid climate is again suggested by the presence of a peculiar fish, rare in the Keuper, but common in the succeeding Rhaetic Formation, known as *Ceratodus*, whose present-day descendant is *Neoceradotus* (Queensland Mudfish), a creature especially adapted by the development of lungs to survive long droughts, when buried in the mud of a dried-up river. It is not known, however, whether the Triassic form had this adaptation.

That at times and in certain places there were more favourable conditions of life, is shown by the fair abundance of both plant and animal remains referred to above as occurring in the Keuper Sandstone round Bromsgrove [1] and at Warwick. The presence of scorpions amongst the terrestrial animals found at Bromsgrove is of interest as evidence of the type of climate then prevailing; for the group at the present day is highly characteristic of hot regions enjoying either seasonal or low rainfall. Bones and teeth of large amphibians (Labyrinthodonts) also occur here and elsewhere; it will be recalled that all amphibians must pass the earlier stages of growth in water, and consequently their occurrence in the Keuper Sandstone necessitates the introduction of water into our picture, at any rate at certain seasons. Fossil footprints are fairly common at various localities, and judging from them there must have been a considerable variety of terrestrial animals, of which we know nothing else.[2]

Several bizarre horned forms have been unearthed at Elgin in Scotland.

Only a few species of fossil-plants are known from the British Keuper, and these throw little light on the environment beyond the fact that two at least (*Schizoneura* and *Equisetites*) belong to the Marestail family, and probably grew in or very near to water. A conifer called *Voltzia* had winged pollen-grains for wind-dispersal.

The Marls of the Upper Keuper.—The great expansion of the area of deposition in Upper Keuper times and the consequent development of basal breccia where the marls lie directly on the ancient hills have already been dealt with. It is now proposed to see what was the environment in which this very remarkable and very thick series of marls originated.

The most striking feature is the persistence from Ireland to Alsace and Bavaria of a distinctive and, one might almost say, unique type of rock. For this to come about there must have been a remarkable uniformity of level and of conditions over this large cuvette.

A varied repetition of a small selection of peculiar rock-types through a thickness of hundreds of feet makes a description of the

[1] L. J. Wills, *P.G.A.*, vol. xxi, 1910, pp. 249–331, and *Proc. B'ham Nat. Hist. and Phil. Soc.*, vol. xiv, Pt. I, 1915, pp. 1–16.

[2] H. C. Beasley, *Reps. Brit. Assoc.*, 1903 to 1909.

formation a matter of difficulty; but it consists essentially of chocolate-red, calcareous mudstones, occasionally blotched or striped with green. These alternate with more sandy bands,[1] usually of a grey or green colour. The red bands often show very little sign of lamination, though the whole series is well-bedded. Bosworth, who investigated their composition in Leicestershire, found that they consisted chiefly of excessively fine particles of an argillaceous mineral, fine quartz-silt, and extremely minute rhombs of dolomite. This last constituent had also been detected elsewhere by Cullis. Lomas, on the other hand, described the marls as composed almost exclusively of exceedingly fine and angular quartz-dust. Possibly the material varies with the locality.[2]

The green sandy bands are known as "skerries." They usually consist of seams of several different kinds, generally including grey marl and grey sandstones or siltstones varying from dolomitic sandstones to quartzose dolomites. The two latter differ in the proportions of quartz and dolomite-rhombs.[3] The latter, though in some varieties it may have formed in place, is usually abraded and derived like the quartz-grains from the denudation of some other deposit.[4] Dolomite may make up as much as 35 per cent of the rock (e.g. in some hard grey crystalline varieties). The grey sandstones may display irregular bedding, casts of sun-cracks and footprints, pseudomorphs after rock-salt,[5] and ripple marks, all indicating an origin in shallow sheets of water that were liable to dry up. Some of the sandstones are also of the "millet seed" æolian type (p. 113). In Leicestershire the direction and shape of the ripple-marks suggest the prevalence of winds from between south and west.

In addition to the red marls and skerries, chemical precipitates of gypsum, anhydrite, rock-salt, and celestine are found at various horizons in the Keuper Marl Series. The great size of some of these deposits implies the evaporation of vast volumes of water from exten-

[1] The fairly regular repetition of coarser and finer sediments throughout the Keuper Marls suggests an alternation of wet and dry periods, as the governing factor in their formation (see p. 122).

[2] T. O. Bosworth, *Keuper Marls around Charnwood*, Leicester, chap. xii, and *Q.J.G.S.*, 1912, vol. lxviii, p. 281. C. G. Cullis, *Rep. British Association* for 1907, pp. 506–7. J. Lomas, *Proc. Liverpool Geol. Soc.*, 1906–7, p. 172, and *Geol. Mag.*, 1907, p. 511.

[3] B. Smith, *Geol. Mag.*, 1910, p. 309.

[4] The possibility of direct precipitation of dolomite is strongly supported by the abundance of these rhombs in the Keuper Marl (see note, p. 98).

[5] A salt-pseudomorph is a cast in sandstone of a cubical crystal of rock-salt. Its usual mode of formation is as follows: The salt had crystallized in the top layers of a dried-up mud-flat. On the arrival of the next sand-bearing freshet, the salt was dissolved and the hollow in the baked mud was filled up by sand; and, just as in fossil footprints, it is this natural cast that we find (see p. 85).

sive lakes that were at times reduced to a number of pools of concentrated brine (see p. 103).

Despite their fine texture, there seems no doubt that the Keuper Marls originated in shallow waters, and that these waters were liable to dry up. Yet the deposit may be as much as 3,000 feet, and is commonly 600 to 1,200 feet thick. Its accumulation seems gradually to have been filling the Triassic Cuvette of Britain, France, and Germany, and producing a plain with very low relief. Such plains are found in many deserts. They are liable at certain seasons to be flooded by widespread ephemeral inundations of comparatively fresh water, caused by rainfall on the bordering uplands. The grey skerry bands may be regarded as the coarser deposits of such sheet-floods,[1] which quickly dried up; whereas the red marls were partly formed of the finer material laid down in the intervening dry periods in the still, salt waters of more permanent lakes and playas, and partly of dust blown into the lakes or arrested on damp salt-impregnated surfaces. The hills that encircled the cuvette and rose above its level floor were covered with angular desert-talus, and around them delta-fans of gravel, grit, and sand were spread out on the plain, which at certain seasons was dotted over by playas and at other times was a grilling sun-baked desert. The general aridity is perhaps most strikingly evidenced by the abundance of crystals of dolomite (p. 121), which must have been precipitated either on the evaporation of the playas or subsequently in the interstices of the sediments as they dried; and by the massive salt, gypsum, and anhydrite deposits which by their bulk witness to the final desiccation of the larger, more permanent lakes. The large volume and widespread occurrence of beds of gypsum and of rock-salt at particular horizons seem to imply periods of extreme aridity, but at the same time they suggest that a great part of the British Keuper cuvette was at one level, and capable of being covered by a single sheet or perhaps a few smaller sheets of shallow water.[2] This latter feature is borne out by the occurrence towards the top of the Marl Series of a thin bed of fossiliferous sandstone (Arden Sandstone) that covers a large area in the Midlands, and by the similar widespread occurrence of gypsum at certain levels.

It is uncertain whether this Arden Sandstone with its fragments of land-plants and animals, and the teeth, spines, and scales of Ganoid fishes, records an extensive lake or an arm of the sea; for although the fossils show that it was sufficiently fresh to support a considerable number of fish, they do not declare decisively for one or other environment. If it was an incursion of the sea, and various facts

[1] Compare the "sheet-floods" of the Western States of U.S.A. and of West Australia, as pointed out by B. Smith, *Geol. Mag.*, 1910, pp. 302–11.

[2] R. L. Sherlock, *Geol. Mag.*, 1918, p. 120.

point to this, it was short-lived; for the sandstone is only some 25 feet thick, and is succeeded by 120 feet of the usual barren red marls before the succeeding marine Rhaetic Beds are reached. Outside the Arden Sandstone there is practically nothing known of the Upper Keuper fauna and flora, *Estheria* (p. 116), and one or two footprints having alone been found.

Having the Keuper Marl in mind, Walther, probably the widest-travelled investigator of modern deserts, confesses that for long he could find no modern parallel to explain the formation of the red marls. "I was therefore as much surprised as delighted when I saw before my eyes in the West Australian desert how such marls can come into being. . . . On the gently undulating plateau about 400 m. above sea-level lay a covering of laterite formed through the weathering of iron-bearing rocks. It had been intensely denuded ever since Pleistocene times. The laterite plateau, bordered by desert mountains and cut through by wadies . . . was surrounded by a lower-lying marginal region ('the Under-plateau') that appeared on the maps to be covered by large and small lakes. After year-long droughts, deep barometric depressions occasionally spread over this almost completely rainless region, and unburden themselves of colossal rainfalls. On May 3, 1890, there fell at Fortesque 70 cm. of rain; from February 17–19, 1896, at Thangoo 75 cm.; on April 3, 1898, at Whim Creek 90 cm. One must imagine what it means when in the midst of an arid desert . . . such a volume of water falls in a few hours, and then begins almost at once to evaporate. . . .

"The water saturated with the red laterite mud and with salts leached out from the desert-surface by the weathering processes, rushes down like a Noah's flood over the broad plain. Though in its passage it cannot round the rock-fragments which it snatches up, yet it carries them along to its wide stony delta, beyond which the red muddy water spreads out as a lake. One forces one's way over the stony ground and through the leafless scrub of *Mulga*, and stands suddenly on a measureless carmine-red plain. One sees neither suncracks nor tracks on the salt-impregnated clay which balls in thick soft lumps on the feet. The topmost layer formed by the last cloud-burst lies before one completely dry as a result of the great evaporation. . . . These West Australian 'lakes' have a diameter of from 1 to 100 km.; their shape sometimes recalls a wide flood-plain, sometimes a round lake. According to the lengthy observations of J. T. Jutson, the pans change their shape and position from year to year. Dark rock-islands rise above them, and their banks are bordered sometimes by the steep edge of the laterite-plateau, sometimes by red sand-dunes. . . . Here then, far from the sea and high above its surface there are being formed bedded red marls, the thickness of which is

limited only by the continuance of the arid climate under the influence of which a laterite surface has been weathered by the wind, transformed into red dust, and once more deposited in wide pans through the action of occasional cloud-bursts." [1]

If we grant the fairly level surface, the aridity, and the occasional cloud-burst, the height above sea-level is immaterial. In the case of the Keuper the plains must have stood almost at or possibly even below sea-level; for the sea in which was laid down the next-succeeding deposit, the marine Rhaetic Formation, spread rapidly from the southern ocean (Tethys) over the whole of the Keuper cuvette, including Germany as well as Britain.

[1] J. Walther, *Gesitz. d. Wüstenbildung*, pp. 293–4.

IV. A STUDY OF EPEIRIC MARINE ENVIRONMENTS

CHAPTER X

THE GENERAL GEOGRAPHY OF THE JURASSIC SYSTEM

The Jurassic Epeiric Seas of the British Region.—The Hercynian continent which has provided us with the materials for our studies of a dry continental environment was at the end of Triassic times so far levelled that over wide stretches it was easily invaded by the Jurassic sea.

The ancient "Atlantis," however, persisted as land over the present North Atlantic Ocean, with broad promontories over Scotland, Ireland, Wales, and Cornwall; while the whole region stretching south-eastwards from it as far as the northern limits of the geosynclinal sea of Tethys (i.e. approximately the northern edge of the present Alps) remained during the whole of Mesozoic times as a great continental block. Rigid by reason of its substratum of hardened and compacted rocks, this region was mainly affected by epeirogenic movements: sometimes the seas that in Jurassic and Cretaceous times spread over it (Figs. 51, 70, 72) were gradually deepened; sometimes the reverse took place, and new lands emerged. For these reasons the seas must be classed as *epeiric*, perhaps at times *shelf-seas*, at other times *epicontinental* (see p. 47). The deposits are mainly *neritic*, but they vary between deep-water or bathyal types on the one hand, as in some of the great clay-formations and the Chalk, and shallow water, littoral and even terrestrial types on the other hand (coral- and shell-limestones, sandstones, conglomerates, coals, etc.).

Probably the South China Sea with its varying depths and currents, muddy river-mouths and coral-girt islands offers, as far as conditions governing deposition are concerned, the best present-day analogue to the Jurassic and Lower Cretaceous seas of Western and Central Europe;[1] the deeper-water deposits of the Upper Cretaceous (especially the Chalk) were possibly formed under conditions that can nowhere be paralleled at the present time.

There seems to have been no definite barrier between the Mesozoic

[1] It is doubtful whether the China Seas have been produced by the epeirogenic submergence of part of a continent. A. Wegener, *Origin of Continents and Oceans*, pp. 178–82.

seas of North-Western and Central Europe and the waters of Tethys, just as there is none between the China Sea and the Pacific Ocean; but the deposits laid down in the two regions were, as already pointed out (p. 105), very different in type. Those belonging to Tethys need not here be discussed.

We are more particularly concerned with the British Isles, which

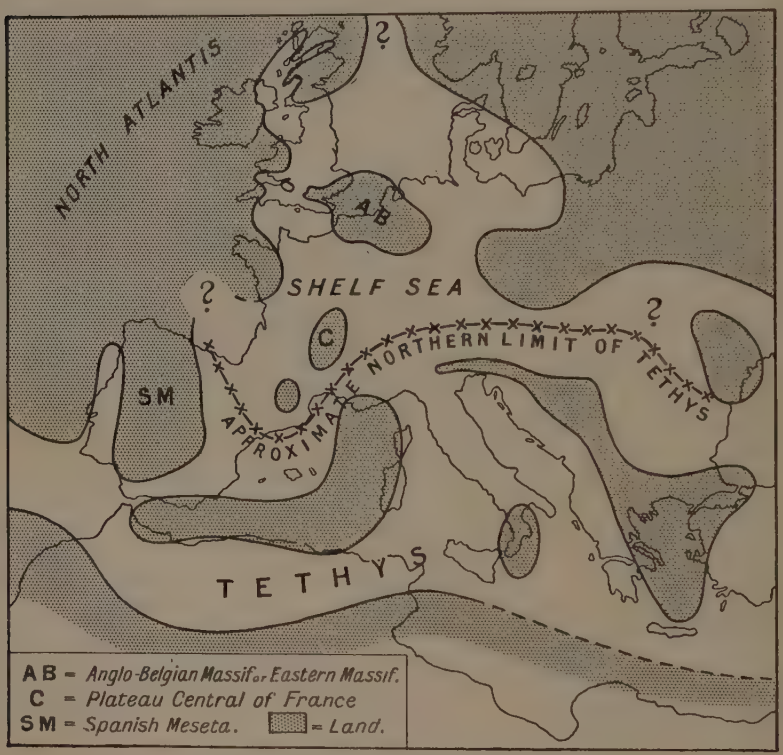


FIG. 51.—Europe in Lias times.
Land stippled. After Haug, Arldt, and Stamp.

at the beginning of the period lay below a shelf-sea. The lands bordering it were mostly low-lying, and the waters that lapped against them were nowhere very deep, both these features being the result of the prolonged continental erosion combined with the deposition that had taken place in the preceding periods; for the Triassic geography was passed on to the Jurassic unmodified by any important earth-movement. The main land-masses were to be found in approximately the same regions which had stood out above the Keuper area of deposi-

tion: viz. the Western Massif over most of Ireland, Wales, Cornwall, Brittany, and the adjoining seas; the Northern or Caledonian Massif over much of Scotland and Scandinavia; and the Eastern Massif extending from the Thames basin into Belgium and Northern France (p. 82). While the first two were probably projections from the northern continent of Atlantis, this Eastern Massif was probably a large island, as was also the massif of the Central Plateau of France, During a prolonged period like the Jurassic, the limits of the land and sea must have varied indefinitely, but the presence and general permanence of the three massifs exerted an influence that can be observed throughout the British Jurassic strata (see the maps, Figs. 54, 61, 68, in the sequel).

The Effects of slight Isostatic Movements on Neritic Deposition.—At present the main Jurassic outcrop runs from Dorset to Yorkshire, but there are outlying patches which show that the formation originally covered most of England and extended into Ireland and Scotland. The map (Fig. 54*a*) indicates approximately the areas of land and water in Lower Jurassic times (Lias). As already pointed out, the geography varied greatly within the Jurassic period, but in general it may be stated that the maximum development of the system (as in the case of the Trias) was in the Midlands and in the southern counties, in cuvettes whose floors were continually sinking; whereas there was a tendency throughout towards uplift and erosion in the east in the area of the Eastern Massif.[1] This is shown by the following facts. Many of the rock-sheets extend for long distances from south-west to north-east, and in certain cases throughout the entire length of the country from Dorset to Yorkshire; but if the underground continuation of any bed be examined, it will be found to thin and gradually die out in the direction of the present Thames valley (Fig. 52). In the case of the higher beds this is partly due to the bevelling and destruction by erosion that they underwent before the deposition of the overlying Cretaceous, but in the lower members of the formation the thinning out of the individual sheets is original.[2] It will be recollected that the thinning out and consequent lenticular nature of the subdivisions of the "continental" Triassic rocks was even more conspicuous in the same area and in the same direction (Fig. 42).

[1] The absence of the Jurassic under London and North-East Kent has considerable practical interest; for it contributes to the possibility of borings and shafts reaching to the platform of Palæozoic rocks (including the Coal Measures) on which the Mesozoic formations rest. Had the Jurassic system retained the thickness which it possesses in the Midlands, the Kent coals would be completely out of reach (see p. 197).

[2] G. W. Lamplugh, *Proc. G.S.*, vol. lxxv, 1919, pp. lxxiii–xcv.

Though many of the stages in the Jurassic persist along the strike right across England, their thicknesses vary very greatly in this direction also. The section (Fig. 53) shows clearly that the thinning

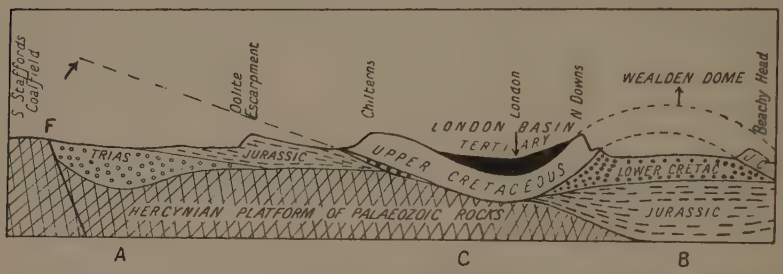


FIG. 52.—Diagrammatic section from S. Staffordshire Coalfield, south-east to London, thence south-south-east to Beachy Head.

A and B, regions of maximum Mesozoic sedimentation (negative elements); C, the Mesozoic Anglo-Belgian or "Eastern" Massif (positive element); F, fault.

occurs in the Lower and Middle Jurassic over the Mendips, Oxfordshire, and South Yorkshire; and that in the upper part of the system it is confined to Bedfordshire and South Yorkshire.

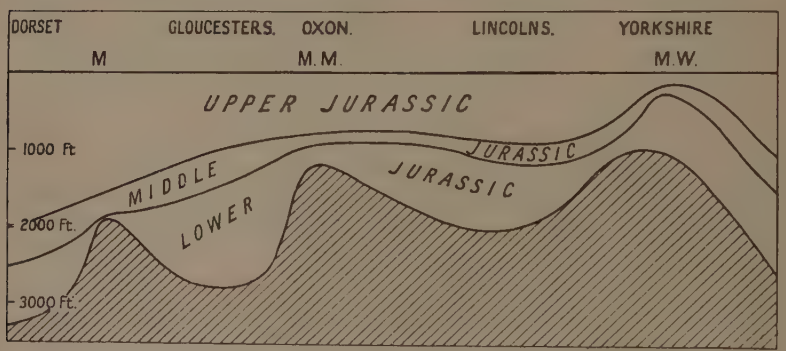


FIG. 53.—Diagram to show Lateral Variation in Thickness in the three divisions of the Jurassic, due to contemporaneous movement of the sea-floor.

Anticlinal axes of M., Mendips; M.M., Moreton-in-the-Marsh; M.W., Market-Weighton.

In the intervening districts there was a tendency to downward movement that kept pace with the deposition of a thick pile of sediment; whereas the floor of the sea in the areas named underwent less rapid downward, or even slight upward, isostatic movement (p. 8), implying the shallowing of the waters in those regions, so that at times shoals, reefs, and islands appear to have been formed. Under

TABLE VI. The Jurassic System.

Epoch.		Lithology.			
		South-West England.	Yorks and Lincs.	Western Scotland.	North-East Scotland.
Upper	Purbeckian	Freshwater passage-beds to the Cretaceous	Marine clays	Not known	Not known
	Portlandian	Sandstones and limestones [2]	Absent		
	Kimmeridgian	Dark, often bituminous,	shale and cementstones	Not known	Marine shales, limestones and sandstones with an estuarine intercalation
	Corallian	Limestones and clay	Limestones	Not known	Estuarine white sandstones and marine limestones and shales
	Oxfordian	Dark clays	Dark clays	Dark clays	Marine sandstones and sandy clays
Middle	Bathonian [1]	Oolitic limestones and marly clays	Estuarine sandstones, limestones and shales, marine in part	Thick estuarine and freshwater deposits in places	Estuarine deposits
	Bajocian [1]	Oolitic limestones, some ironstones and sandstones	Estuarine sandstones and shale with marine limestone intercalations	Some marine sandstones and marls	Estuarine deposits
Lower	Liassic	Blue-grey clays with thin beds of cementstone and bands of ironstone		Marine sandstones and shales	Estuarine and marine deposits
	Rhætic	White limestones and blue shales. Black shales with bone-beds, and grey shales or conglomerate at the base	Black shales and a bone-bed	Calcareous sandstones, limestones and shale (the whole very thin)	

[1] These terms have been employed in various ways. As used here, Bajocian may be taken to be equivalent to the Inferior Oolite Series, and the Bathonian to the series between the Fuller's Earth and the Cornbrash, inclusive.

[2] Except where otherwise stated, the strata are marine in origin.

such circumstances sedimentation is much interfered with by wave- and current-action, so that the deposits of any particular time-period tend to be thinner here than elsewhere. That the Jurassic rocks contain the record of these major movements and of a number of more subordinate and local oscillations will be seen in the sequel.

Classification of the British Jurassic.

Although all the British Jurassic strata are fairly shallow-water deposits, and though most of them are marine, a very great variety of rock-types are found. Table VI shows the main time-divisions and the corresponding general lithological characteristics of the strata.

It will be seen from the table that, broadly speaking, in the Liassic, Oxfordian and Kimmeridgian epochs there were deposited in Britain great clay formations, representing fairly deep muddy seas of the bathyal type. The intervals between these epochs were marked by shallower- and clearer-water conditions in which organic and oolitic limestones were the principal types of deposit except in Yorkshire and Scotland, where estuarine and deltaic sediments record proximity to a northern land. Towards the very end of the period general uplift took place so that deposition was almost limited to the southern counties, and was here estuarine in type.

A detailed account of the varying environments in which the Jurassic strata originated is given in the succeeding chapters.

CHAPTER XI

THE LOWER JURASSIC ROCKS

The classification adopted here (p. 129) is:

Liassic. . . .	Mostly blue shale with or without thin limestones. Locally ironstones and sandstones.
Rhætic.[1] . . .	Mostly dark shales and white limestones.

The Rhætic Formation

The Passage from the Triassic to the Jurassic Formation.—It has already been pointed out (p. 124) that the continental deposits of the Keuper are everywhere succeeded by the peculiar marine sediments of the Rhætic Formation which consists of black shales with some bone-beds and white limestones. The rocks are characterized, not only in this country, but on the continent, by peculiar dwarfed fossils. The paucity of species and their general stunted nature, the occurrence of terrestrial animals in the bone beds, and the numerous signs of contemporaneous erosion are all features of the Rhætic strata which suggest that the sea was shallow and very land-locked.

For our purpose the chief interest lies in the evidence afforded by the Rhætic of a very widespread epeirogenic movement (p. 8) that led to a submergence of a great part of the Hercynian continent. During the Trias, the open sea had been limited to the Mediterranean region, there being, even in Muschelkalk times, a partial barrier (Vindelician Mountains of Gümbel: Fig. 41) between the waters or Tethys (see p. 73) and the area of deposition of the "Continental" of "Germanic" Trias.[2] With the advent of the Rhætic, a northward

[1] The Rhætic is sometimes classified as Trias, but many regard it, on account of its marine origin, as the lowest member of the Jurassic. The latter course is adopted here.

[2] E. Suess, pointing out the presence of the "Germanic" facies of the Trias in various parts of the Western Mediterranean, states that the notion of a long range of Vindelician mountains is untenable (*Face of the Earth*, vol. iv, p. 223). That a range existed in Southern Germany seems fairly well proved, though it may have been a worn-down stump of one of the Variscan Chains that formed a land-barrier, rather than high mountains. For full discussion, see W. Pfeiffer, *Das vindelische Land*, "Erdgeschichliche Abhandl. aus Schwabe u. Franken," *Geol. u. Geogr. Inst. Universitat Tübingen*, Heft 5, 1923. E. Hennig, *Geol. v. Württemberg*, Figs. 9, 12, 14, 22.

extension of the waters of Tethys in the region of the Jura mountains carried the sea across Europe as far as Scotland and North Ireland. Its transgression into the German Keuper basin perhaps denotes the subsidence of Central and Northern Europe, though it is equally possible that the region invaded was already below sea-level, and that the waters of Tethys were admitted by the breaching or depression of some Vindelician barrier. The sudden change of lithology and fauna at the base of the Rhætic that is found practically everywhere would accord with this view.

A persistent feature of the Rhætic formation is the occurrence of black, finely laminated shales (Contorta Shales) with dwarfed fossils. It is a remarkable fact that a few of these peculiar fossils, e.g. *Avicula* (*Pteria*) *contorta*, *Schizodus ewaldi*, *Pecten* (*Chlamys*) *valoniensis*, are found right across Europe from the Tyrol to Ireland. There is also a complete absence of Ammonites which are so characteristic of the true marine deposits of the Jurassic.

The following considerations may throw light on the possible conditions governing the deposition of these shales. The sudden invasion of a low-lying continental area would produce a very land-locked sea in which free connection with the open ocean would be difficult. This would probably be expressed by an abnormal salinity that would exclude all save a few hardy forms of life, and these might well be dwarfed by the inclement surroundings. The shallownes of this great inland sea would also prevent much circulation of the water, so that little life, except bacteria, could exist on the bottom; and, as in the present Black Sea,[1] black fetid mud may have slowly accumulated here, for the invasion of the land area by the sea may have greatly reduced the supply of terrigenous detritus.

A second lithological type that occurs commonly at or near the base of the Rhætic is the so-called "Bone-beds." These are conglomerates or breccias, sometimes with quartz-pebbles, but essentially composed of more or less rounded fragments of fish-teeth and scales, and reptilian bones. Frequently too there are nodules of calcium phosphate with iron pyrites. There has been considerable speculation as to the origin of these bone-beds. It seems unlikely that they represent the remains of creatures killed off wholesale by some change in the environment, though this has been suggested. Thus Jukes-Browne thinks that they record the destruction of the creatures that had entered the Keuper cuvettes with the incursion of the Rhætic sea, and there found new and peculiar conditions which were inimical

[1] As suggested by P. F. Kendall and H. E. Wroot, *Geol. of Yorks*, p. 292. For conditions in Black Sea, cf. *Guide to the Excursions of the VII International Geol. Congress*, Petrograd, 1897, chap. xxix, and J. E. Marr, *Q.J.G.S.*, vol. lxxxi, 1925, p. 125, and discussion on same.

to life. Their remains would be mingled with those of the terrestrial plants and animals of the Keuper cuvettes. More probably, however, they are accumulations covering a great length of time on parts of the sea-floor where there was very little terrigenous material settling to the bottom to mask the steady accretion of organic debris, much of which was brought by floods from the rivers and neighbouring lands. The absence of the finer sediments, taken in conjunction with the presence of partially-rounded quartz-pebbles, coarse sand, and bones of terrestrial animals, suggests that they were formed at no great distance from the land in places where there were currents capable of removing the finer detritus, but unable to cope with the larger material which in this way became relatively concentrated (see "Aggregate beds," p. 140).

In South Wales and Eastern Somerset we have a record of the borders of the Rhætic Sea preserved in the deposits. In South Wales there is but little break between the Rhætic and the Keuper, but the former overlaps the latter (see Fig. 47), so that the littoral deposits of the Rhætic lie directly on Carboniferous Limestone. The typical black shales pass in the direction of the ancient coast line first into massive oolitic limestone suggestive of a hot sea well supplied with calcareous mud from the erosion of the Carboniferous Limestone forming the neighbouring land, and finally in the vicinity of Bridgend into massive sandstones that mark the actual shore.[1]

In Eastern Somerset (Mendips) there are also littoral deposits consisting of thin conglomerates, sometimes with limestone pebbles bored into by worms (*Polydora*) (as in beach pebbles round our coasts to-day), sometimes with numerous bones and teeth of vertebrate fossils. The beds lie on a channelled surface of, and often fill in fissures in, the underlying Carboniferous Limestone.

The waters of this peculiar Rhætic sea must gradually have expanded, deepened and so assumed a more open-sea character, while the surrounding country ceased to be a desert; for the upper Rhætic sediments are mainly white limestones which pass upwards imperceptibly into the clays and limestones of the Lias, which teem with the remains of marine life. Even in the Upper Rhætic there are abundant insects in certain of the limestones. The expansion of the Rhætic into the larger Liassic sea is recorded in South Wales by the fact that the Liassic rocks extend beyond the limits of the Rhætic (Fig. 47). Elsewhere, however, evidence of the expansion has usually been destroyed by subsequent erosion.

[1] A. H. Cox, *Proc. Geol. Assoc.*, vol. xxxi, 1920, p. 74 (see also p. 134 below).

The Liassic Formation

Facies and Environments.—Imagine well-watered and gently undulating lands teeming with plants and animals, drained by large rivers turbid with mud and sand, and discharging their burden of sediment, organic debris, and soluble salts into an open but not very deep sea in which life abounded. Such is the picture of the Lias.

The probable distribution of land and sea in Lias times is shown on Figs. 51 and 54*a*, but only here and there have we actual records of

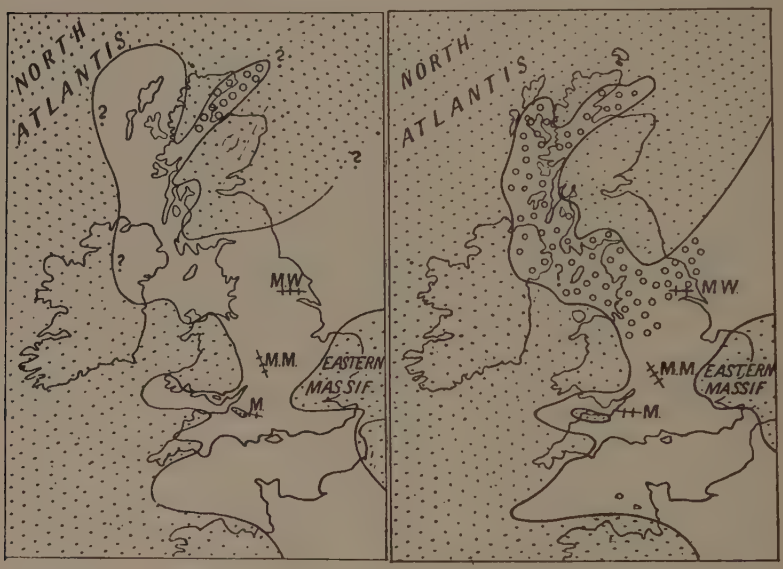


Fig. 54.—(*a*) Liassic Geography. Based on Haug and Stamp. (*b*) Bathonian Geography. Based on Jukes-Browne, Haug and Arldt.

Rings indicate deltaic deposits; land stippled. Anticlinal axes of M., Mendips; M.M., Moreton-in-the-Marsh or Oxfordshire; M.W., Market-Weighton.

the coast-line of the continent that lay to the north and west. For example, in South Wales the Lias deposits, like the Rhætic, were laid down near that shore, and exhibit features dependent on its nature. Here near Brigend the coast was bordered by islands made of Carboniferous Limestone, and the littoral facies of the Lias consists of *detrital limestones* (p. 39) built up of fragments riven from the old cliffs, and washed from the neighbouring country. The blocks show signs of having been rounded by the solvent action of the sea-water. They are set in a matrix that was once a fine calcareous detrital mud which is now, however, often recrystallized into a calcite-

cement.[1] These limestones are known locally as "Sutton Stone" and "the Southerndown Beds." The former was formed inshore, and often contains an abundance of corals. These littoral rock-types should be compared with the corresponding deposits of the Keuper and Rhætic (pp. 111, 133). It will be noted that the Liassic deposits overlap the others, and thus indicate that the area of deposition was hereabouts more extensive than in the Trias and Rhætic periods (Fig. 47).

In Lower and Middle Lias times the Eastern Mendips stood up as islands or shoals in the sea, for the lower beds are very thin and display littoral characteristics, or are absent altogether (Figs. 53 and 54*a*, M).

The geography of the Bristol Channel region must have been very similar to that obtaining in Keuper times (p. 112), except that the sea now occupied the cuvette and lapped against islands that formerly had probably been "inselbergs" (p. 112 and Fig. 46).

In general, however, the major part of the Lias Formation is composed of dark shales, limestones, and cementstones, which we may examine as deposits formed principally in the "blue-mud" zone of an epeiric sea (p. 47). The Lias clay is more often a fissile shale than a plastic clay. Its dark grey or blue colour has been doubtfully claimed in some instances to be due to its derivation from the erosion of Coal Measure clays; but in most cases it is produced by finely disseminated iron-pyrites.[2] Occasionally the colour denotes that the rocks are highly bituminous, and they may even approach the composition of oil shales (e.g. in Somerset).[3] It is uncertain how far the organic matter is derived from plants and how far from animal remains.

The Lias clay abounds in fossils. The majority are remains of marine creatures that throve on the muddy bottoms of a sea into which rivers brought much organic debris and terrigenous mud. Such in particular were the Ammonites and Belemnites (see p. 62), whose remains are peculiarly characteristic of clays that accumulated under fairly deep-sea (bathyal) conditions. Yet the discovery in some places of complete skeletons of the larger marine reptiles has been taken to suggest that locally at any rate the water

[1] A. E. Trueman, *Proc. Geol. Assoc.*, 1922, vol. xxxiii, pp. 255–9.

[2] Giekie states that "the chemical changes that result in the elimination of sulphides from sea-water may be explained by supposing that the decomposing animal and vegetable matter on the sea-floor reduces the sulphates to sulphides, which in turn react on the iron and manganese minerals (principally silicates) in the mud, forming sulphides of these metals."

[3] The oil-yield is, however, small and spoilt by the high percentage of sulphur (see H. G. Shatwell, A. W. Nash and J. Ivor Graham, *Journ. Inst. Petroleum Technologists*, vol. x, 1924, No. 47).

was shallow enough for these monsters to strand, so that the whole body rotted away in one place. In certain bands insect-remains tell of fertile shores not far distant.

In many parts of the Lias *concretionary limestones*, *septarian nodules*, and thin bands of earthy limestone or *cementstone* are found in the clays. The Lower Lias in particular consists in some places of rapid alternations of shale and cementstone.[1] These various types of limestone and cementstone are fine-textured, generally flaggy and often unfossiliferous, and are very different from the Magnesian Limestone discussed in Chapter V, and from the organic limestones and oolites to be described below (pp. 146–8). H. B. Woodward claimed the cementstones as hardened calcareous muds derived from the erosion of older limestones; but their secondary origin has been urged with perhaps more convincing arguments by W. A. Richardson.[2] On his view, while the sediment was still comparatively unconsolidated, the calcareous substances in solution in the water that permeated the whole formation have been precipitated within the body of the rock in thin bands having a rhythmical spacing, thought to be due to the same causes that produce the alternately salt-rich and salt-free bands of "Liesegang's Rings." In some places there are thin veins of fibrous calcite, known as "beef," the veins lying parallel to the bedding. These also appear to represent calcium carbonate precipitated during the consolidation of the rock.

The *bedded ironstones* of the Jurassic are the most important sources of iron-ore in England and France. The principal occurrences are *either* in the Lias, viz. the Lower Lias ore of Frodingham, Lincs., the Middle Lias ores of Cleveland (Yorkshire), Leicestershire, and Oxfordshire; *or* at the junction of the Lias and the Bajocian, viz. the Dogger Ores of Yorkshire, the Northampton Ironstone of Northamptonshire and Rutland, and in Belgium and France the Minette Ores of Luxembourg and Lorraine.

In general these bedded ores [3] are marine chemical precipitates. Most of them consist of a ground-mass of the finely crystalline or amorphous chloritic mineral called chamosite (alumino-silicate of ferrous iron) throughout which are scattered small crystals of siderite (ferrous carbonate). Sometimes ooliths (p. 146) of chamosite are present. This ground-mass also often contains sand-grains and fragments of shells and other organic debris; and calcite as well as siderite may also occur as a cementing medium. When unaltered by

[1] The two being used together for making cement.

[2] W. A. Richardson, *Geol. Mag.*, 1921, p. 120, and *Q.J.G.S.*, vol. lxxix, 1923, pp. 95–7.

[3] A. F. Hallimond, "Iron Ores, Bedded Ores of England and Wales, Petrography and Chemistry," *Spec. Rep. Min. Resources Great Britain*, vol. xxix, *Mem. Geol. Surv.*, 1925. This contains references to recent literature.

weathering the ores have a characteristic blue-grey tint, due to the colour of the *chamosite*; but normally, as exposed at the surface, they have the yellow-brown hue of the limonite that by oxidation and hydration has replaced the chamosite. They are then frequently full of cavities and cracks, and relatively richer in iron. Perhaps the most striking feature of the ironstones is the constant recurrence of structures that indicate contemporaneous current-erosion. For example, sometimes they include coarse breccias composed of broken pieces of other ironstones, and at other times they are largely composed of bits of water-worn shells, and of ooliths and sand-grains that have evidently been drifted along the bottom. The arrangement of the ooliths makes it clear that they were transported and graded by currents exactly as if they had been sand-grains.

Recent research has shown that the iron-bearing minerals in the ores were all deposited on the sea-floor in much the same state as we see them to-day. It was formerly thought that they were the products of metasomatic changes in the rocks, by which original calcium carbonate had been converted into ferrous carbonate, but there now seems conclusive evidence [1] that the ferrous minerals, chamosite and siderite, were precipitated directly from supersaturated solutions on and in the material composing the sea-bed.[2] It is possible that the precipitation may have been facilitated by bacteria and algæ, which may have also produced the surroundings requisite for the formation of ferrous instead of ferric minerals.[3]

This chemical precipitation at times gave rise to oolite-grains where the particles were kept in motion by the waves, just as in the case of calcareous ooliths (p. 186). Elsewhere chamosite muds were formed. Probably the formation of the iron-ores went on in shallow seas where waves played an important part in breaking up the sea-bed into gravel and sand, and in keeping these products and the precipitated ooliths in motion, thus sorting and grading them.

At other times more tranquil conditions allowed the deposition of ferrous muds to cement and augment the material on the sea-floor, thus producing an ironstone. In purer varieties the singular freedom from terrigenous detritus shows that the sea in which they were precipitated must have been screened in some way from river-borne

[1] A. F. Hallimond, *op. cit.* L. Cayeux, *Introduction à l'étude pétrographique des roches sédimentaires*, Paris, 1916. For the older metasomatic theory, see papers by Sorby, and a concise account in Hatch and Rastall, *Textbook of Petrology: The Sedimentary Rocks*, p. 199.

[2] This statement does not preclude the possibility of pene-contemporaneous secondary chemical reactions having taken place on the sea-floor.

[3] It is interesting to note that up to now similar ferrous precipitates have not been observed in any dredgings from the present ocean-bed.

sediments (p. 134).[1] Yet deposition cannot have taken place too far from the mouths of rivers, for it is to them that we must look for the renewal of the supply of iron salts which ultimately are derived from the chemical weathering of the land. Such specialized conditions of the sea-floor must be accounted for by peculiarities of contouring, currents and coastal surroundings. Many of the ores are interbedded with, and pass laterally into, clay; and it seems likely that the presence of ironstone [2] instead of clay must be connected with the cutting off of the supply of terrigenous sediments by changes of the currents or by the alteration of the mouths of rivers entering shallow, almost lagoon-like seas. Such changes are quite in keeping with those discussed below which have given rise to non-sequences (p. 63).

Contemporaneous Movements and Non-sequences.—Everywhere the Lias presents a wonderfully uniform series, unbroken by obvious gaps. Many of the original, broadly defined palæontological zones can be identified from the Hebrides to the Jura Mountains in their appropriate order and with their characteristic fossils. But the apparent simplicity is deceptive. When the sequences in different parts of the country are correlated with one another by the exact zonal methods discussed in Chapter V, it is found that in no case is there a complete record. Some of the small sharply-defined zones are present here that are absent there; others are common to two districts, but elsewhere are found separated by yet other zones. *Non-sequence* is the name given to such gaps in a sequence which can only be detected by zonal methods, and which as a rule involve no visible sign of unconformity or, at most, only slight indications that pass unobserved until notice is called to them by a study of the fossils (see Chapter V, p. 63).

[1] See, however, J. G. A. Skerl, "Petrography of the Northampton Ironstone," *Proc. Geol. Assoc.*, vol. xxxviii, 1927, pp. 375–93, espec. p. 388, where the probable effect of the entry of a river into the lagoon-like sea is claimed to be seen in a sideritic instead of a chamositic ore.

[2] One other type of ironstone may be mentioned here, though not typically developed in the Lias. This is the "Limonite Oolite" type. Here the iron is chiefly represented by ooliths of brown limonite, which appear to have been precipitated in the same way as the chamosite ooliths, but in oxidizing, instead of reducing, surroundings. The ooliths are set in a ground-mass which may be a sand (Kellaway's Rock in Kent); a clay like the Claxby ironstone (Lower Cretaceous); a shelly limestone like the famous Frodingham ore (Lower Lias); or a chamosite mudstone as in the Corallian ore at Westbury, Wilts. It will be seen that in the last example ferrous and ferric compounds appear to have been thrown down simultaneously, the proportions of the latter depending on the available oxygen. By increase in the relative proportion of detrital minerals the limonite-oolite ores pass into "iron-shot sands," like those of the Lower Greensand (see p. 163). Similar sands have been identified on the floor of the present North Sea.

The absence of a particular zone or zones may be due to (1) *contemporaneous erosion*, implying generally a certain amount of uplift that brought recently-formed deposits within reach of the erosive action of waves or currents; or to (2) *non-deposition* where currents were strong enough to prevent any sediment from accumulating. This does not necessarily involve an uplift. Observations on the present-day oceanic and tidal currents show that they may in excep-

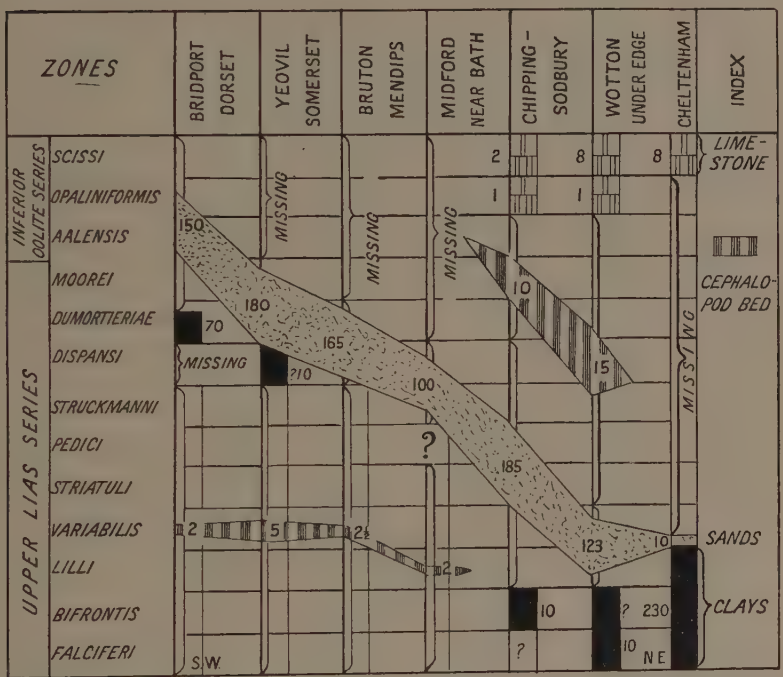


FIG. 55.—Diagram to show the Diachronic Relation of the Cotteswold, Midford, Bridport Sands, and of the "Cephalopod Bed" to the zonal Hemeræ in different districts. Figures give thicknesses in feet.

The hemeræ are shown of equal length (abscissæ). Hemeræ marked missing represent the extent of non-sequences. Diagram based on information provided by Mr. L. Richardson.

tional cases keep the ocean-floor swept clean of mud to depths of 6,000 feet.[1] About 1,500 feet is, however, the more usual limit of such action. There is no reason to suppose that the depth of the Lias seas exceeded the latter figure.

Indications that such conditions obtained during the deposition of some of the Liassic ironstones have been mentioned above (p. 137).

[1] A. W. Grabau, *Principles of Stratigraphy*, p. 244.

Aggregate Deposits and Condensed Faunas.—A second phenomenon produced by current-action is the presence of fossils representative of several zones collected together in a very small thickness of rock. The fossils, being relatively large and heavy, were not swept away by the currents that removed most of the clay, and were concentrated into a foot or two of rock, though in other areas the same forms are spaced out through perhaps 50 feet or more. Such a deposit is said to have a "*condensed fauna.*" [1] If the fossils are collected promiscuously from a band of this type, the laws of zoning appear to be invalidated by the mingling of zonal forms; but with careful collection, inch by inch, the species are seen to occur in their proper zonal order, and the laws are vindicated. There is a tendency towards phosphatization of the fossils and the growth of phosphatic nodules in such deposits, phenomena that are indicative of very slow accumulation of sediment.

The "Cephalopod Bed" in the Upper Lias of the south-west of England is a striking example of an "*aggregate deposit*" with a condensed fauna. This rock is a marly limestone full of ammonites, but the particular species vary from place to place. Despite its general uniformity in appearance, the conditions requisite for its formation must have shifted gradually in the course of time, for the fossils indicate its origin in very different hemeræ as it is traced from north-east to south-west (Fig. 55). At Wotton-under-Edge, near Stroud, with a thickness of 15 feet the bed represents the total accumulation of sediment laid down in seven hemeræ (the very top of the Liassic and base of the Bajocian, as here defined, p. 143); while in Somerset and Dorset it is only 2 feet thick and represents the deposits of six or seven hemeræ well down in the Upper Lias.

Stratigraphical Value of a Sand-Facies: Diachronism.[2]—In South-West England towards the close of Liassic time the deposition of mud gave place to that of sands which are known under various names—Bridport, Yeovil, Midford, Cotteswold Sands, and farther to the north-east the Northamptonshire Sands (p. 141). These sands were originally all grouped together as a single formation overlying the Lias clay, as indeed is the case (Fig. 56). But the oncoming and ceasing of the sandy facies in reality varied considerably in time.[3] Thus if we plot graphically the subzones as ordinates and the geo-

[1] S. S. Buckman, *Q.J.G.S.*, vol. xlv, 1889, p. 440. W. D. Lang and L. F. Spath, *Q.J.G.S.*, vol. lxxix, 1923, p. 85.

[2] W. B. Wright has introduced the term diachronous to describe a lithological unit that is of varying age in different areas, and one therefore that transgresses the palæontological zones (*Rep. Brit. Assoc.*, Oxford, 1926, pp. 354–355).

[3] S. S. Buckman, *Q.J.G.S.*, vol. xlv, 1889, pp. 440–74.

graphical position as abscissae (Fig. 55),[1] the fossils tell us that the sands began and ceased to be deposited far earlier in the Cotteswolds than in Dorset.

Here then is a good instance of the unreliable nature of a lithological change as an indication of stratigraphical position. The top of the Lias clay-facies is not a true stratigraphical boundary between two formations of constant age. The upper limit of the clay in the Cotteswolds corresponds with a horizon well down in the Upper Lias Clays

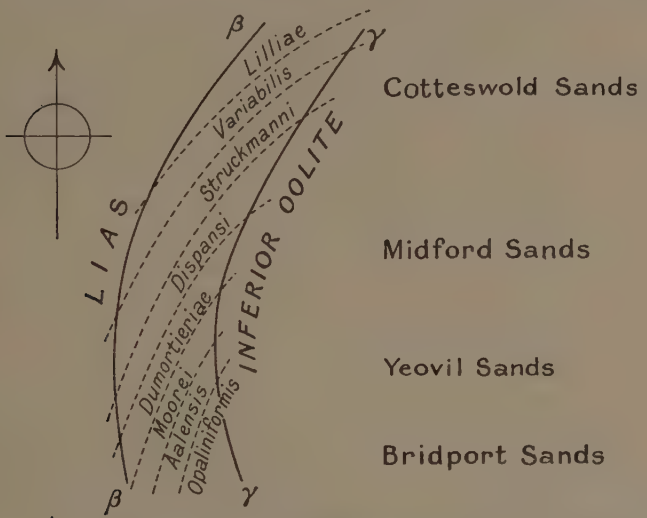


FIG. 56.—Plan of outcrop to show the Diachronic Nature of the Belt of Sands between the Lias and the Inferior Oolite.

Broken lines show limits of the zones. After P. G. H. Boswell.

of Dorset, while its summit in Dorset was formed approximately contemporaneously with part of the Inferior Oolite Series (Bajocian) of Gloucestershire.

The Northamptonshire Sandstones are at a horizon still higher than either (see Fig. 59). Boswell, referring to the Cotteswold-Dorset region, has pointed out that the deposition of this belt of sands of varying ages could have been brought about by the gentle rising and tilting of a shore line, "beginning as a shallow sea in the Cotteswold district, whilst the area of Dorset was submerged under deeper water, and becoming progressively shallow over the belt towards what is now the English Channel." [2]

[1] I am indebted to Mr. Linsdal Richardson for the data on which this figure has been constructed.

[2] P. G. H. Boswell, *Trans. Liverpool Biol. Soc.*, vol. xxxv, 1921, p. 13.

His diagrams (Figs. 56, 57, 58) show how along a coast-line, where in the first case the sea is advancing on to, and in the second case retreating from the land, the divisional planes between lithological facies ("lithological planes") do not coincide with the planes bounding contemporaneous deposits "time-planes." The phenomena in question agree with the second case, and the line $\gamma\gamma$ on Fig. 58 may be taken

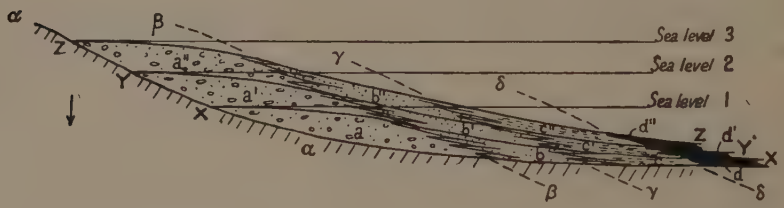


FIG. 57.—Lithological and Time-limits of Rocks formed when the sea-level is rising. α, β, γ, δ, limits of facies *a*, *b*, *c*, *d*; X, Y, Z, time-limits, e.g., of hemeræ. After P. G. H. Boswell.

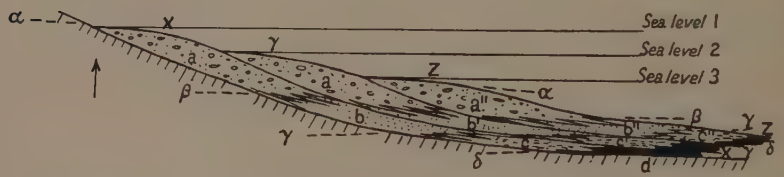


FIG. 58.—As Fig. 57, but with the sea-level falling. After P. G. H. Boswell.

to represent the junction of the sands and the Lias Clay; and though the sands b, b′, b″, vary laterally in age, as do also the clays c, c′, c″, on which they rest, the boundary $\gamma\gamma$ is the one that would be represented on a geological map if it were based on lithology. The time-planes XX, YY, ZZ can only be detected by exact palæontological zoning. Fig. 56 shows the belt of sands between the lines $\beta\beta$ and $\gamma\gamma$, while the transverse lines represent the time-planes that are revealed by a study of the fossils.

CHAPTER XII

THE MIDDLE JURASSIC ROCKS

The classification adopted here (see p. 129) is :

Bathonian. . . . Great Oolite and Upper Estuarine Series. Marine oolite and shelly limestones, and estuarine and freshwater sandstones and clays.

Bajocian. . . . Inferior Oolite and Lower Estuarine Series. Marine oolitic and shelly limestones and clays, and estuarine and freshwater sandstones and clays.

General Physiography.—In general the area where the Middle Jurassic was deposited was much the same as the Liassic seas, but in the north, and perhaps in the east, the land had grown at the expense of the sea, for in Yorkshire and in Lincolnshire deltaic deposits indicate the proximity of the mouth of a great river or rivers that probably drained a land to the north (Fig. 54*b*). In the south and in the Midlands the sea appears to have been shallower, clearer, and possibly warmer than in Lias times. Clays are no longer the predominant type of deposit, but oolitic limestones, shelly limestones and marls, and sandy ironstones (in Northamptonshire) take first place. All these abound in shallow-water fossils, such as brachiopods, corals, molluscs, bryozoa, and sea-urchins, and display structures which indicate that they were laid down under shallow-water conditions or as reefs. Ammonites are occasionally present.

During the period, isostatic movements were in progress that modified the distribution of land and sea, and the depth of water, the effects being far from uniform from place to place (p. 54). Indeed, so shallow was the sea at times that quite small movements of the crust produced marked changes in the environment, which are recorded as rapid changes of rock-type and of fossils, or as thickening, thinning or even disappearance of portions of the sequence. The sections, Figs. 53 and 59, show that during this period movement was taking place along approximately the same lines as in the Lias (compare Figs. 54*a* and *b*, in both of which the axes of uplift are marked, M, MM, and MW), and that the thicker limestone-developments are found chiefly in the areas of subsidence. On the other hand each area of uplift coincides with a remarkable attenuation of the deposits, brought

about by non-sequences of varying importance which are revealed by detailed studies of the faunas. The surface of the planed rock below the non-sequence has in some cases been scoured by currents, and in others bored into by worms and other organisms. This latter state is especially well seen in parts of the Cotteswolds in the non-sequence between the Bajocian and Bathonian, which is in some places so great that perhaps it better merits the name of unconformity; for traced northwards from the neighbourhood of Cheltenham, the *Clypeus Grit* (Bathonian) rests on gradually lower members of the Bajocian until, near Chipping Norton, it directly overlies the Lias. (Figs. 59, 8).

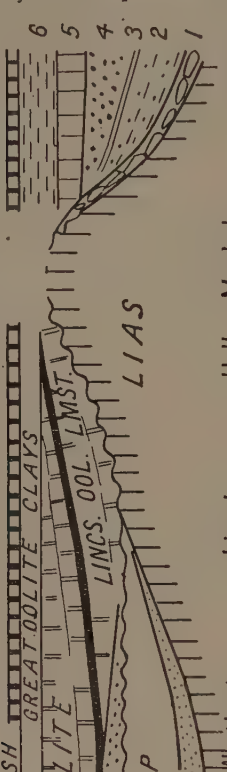


FIG. 59.—Variation in Facies and in Thicknesses, Non-sequences and Gaps in the Middle Jurassic from Gloucestershire to Yorkshire. Certain data from L. Richardson.

1, Dogger (*Murchisonæ*); 2, Lower Estuarine Beds; 3, Millipore Bed (? *discitæ*); 4, Middle Estuarine Beds; 5, Scarborough Limestone (? *sauzei*); 6, Upper Estuarines; 7, Inferior Oolite (*scissi* at base, *sauzei* at top); 8, Clypeus Grit; 9, Black clays, Nœra freshwater beds at N, and "Upper Estuarine Beds" of Northants and Lincs; 10, Fuller's Earth and Stonesfield Slate; 11, Chipping-Norton Limestone; 12, White Sands (? Lower Estuarine Beds); 13, Variable Beds and Northampton Ironstone (*scissi*); wavy line = the main non-sequence. Note that 1 to 5 are roughly equivalent to 7; 6 and 9 probably equivalent, and mark a period of emergence.

The most striking result of the isostatic movements is, however, seen in the alternations of marine and deltaic deposits in the

eastern and north-eastern developments of the English Middle Jurassic. If we follow the outcrop from Oxfordshire to Lincolnshire (Fig. 59), we find the Chipping Norton Limestone of Oxfordshire and the roughly contemporaneous Lincolnshire Oolite Limestone to be separated by an area (Northampton and Rutland) in which the marine deposits are replaced by estuarine sands. Here we probably have evidence of a powerful distributary of the northern river having brought terrigenous matter into an otherwise clear sea. Another distributary was at the same time laying down deltaic deposits in North-East Yorkshire (Lower Estuarine Beds).

At a slightly higher horizon (above the Chipping Norton Limestone) we find the first sedimentary record of land conditions in the form of beds with freshwater shells (Neæran Beds). This deposit is only known from one district in Oxfordshire; but is there followed upwards by black, probably estuarine, clays which extend from Lincolnshire to the Cotteswolds, and mark the maximum extension south-westwards of the deltaic conditions that prevailed in the north-east (Middle Estuarine Beds). The marine Great Oolite Limestone (Bathonian) covers these beds, and shows a re-advance of the sea towards the delta. On the other hand, if we go to North-East Yorkshire,[1] the bulk of the Middle Jurassic series is of estuarine or deltaic origin, but at least three submergences of the region are recorded by marine limestones (Eller Beck Beds, Millipore Bed and the Scarborough Limestone).

Neritic Facies.—The study of the Middle Jurassic of Britain is for our present purpose a study of a variety of contemporary neritic facies, only the more important of which can be here discussed. It will be recalled that *facies* is best defined as the sum of the *lithological and palæontological characters which are presented by a deposit at a certain point.*[2]

We may now see what light a study of a few of the principal facies throws on the nature of the surroundings in which they originated.

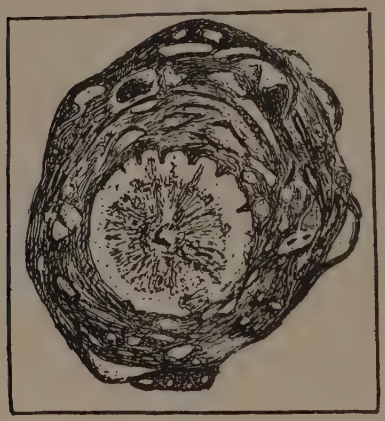
The so-called *Estuarine Beds* are sandstones, dark shales and occasionally coals with underlying soils or seat-earths, and many beds are full of the remains of plants, some of which are still in the upright position in which they grew. The types of rock commonly found resemble closely those characteristic of the Coal Measures, and the conditions surrounding their formation were probably not unlike those outlined in the chapter devoted to the Carboniferous

[1] Owing to the overstep of the Cretaceous and to the movements that have taken place along the Market Weighton axis in South Yorkshire, it is not possible to correlate exactly the Lincolnshire and Yorkshire developments of the Middle Jurassic.

[2] E. Haug, *Traité de Géologie*, 1907, vol. i, p. 145.

(p. 325); but the types of plants found are of course distinctive and quite different from those of the Carboniferous. The characteristics of the Jurassic flora are discussed on page 156.

Turning to marine types, the *oolitic* and *pisolitic* limestones which make up the bulk of the marine Middle Jurassic, are built up partly of bits of shells and other fossils, but mainly of small spherical grains of calcite, set in a fine-grained matrix of the same or of calcareous clay. The name *oolite* (egg-stone or roe-stone) denotes the resemblance of the rock to the hard roe of a fish. Each grain or *oolith*



(*a*)

(*b*)

FIG. 60.

(*a*) Single Spherule or Pisolith of *Girvanella pisolitica* grown round a crinoid ossicle as nucleus. Pea Grit near Cheltenham. (From a photo by E. B. Weathered.)

(*b*) Bath Oolite. Highly magnified. The oolith in the centre shows the typical radial and concentric structure, and crystals growing on its periphery. The other ooliths are almost amorphous. Crystalline calcite between the ooliths.

consists of concentric shells of calcite, often with a radiating fibrous structure (Fig. 60B). Sometimes a fragment of a shell or a grain of sand forms the centre, and has acted as a nucleus of deposition. In *pisolite* (pea-stone) this is usually the case (Fig. 60A). Here the grains are the size of a small pea, and are pierced by minute ramifying tubules that have been claimed to represent the remains of algæ (lowly plants). This rock-type is not common, and the "Pea-Grit" of the Cotteswolds is the best British example.

The origin of calcareous oolites has been investigated by several authors,[1] but even now it is not known whether one explanation

[1] H. C. Sorby, *Q.J.G.S.* vol. xxxv. 1879, pp. 74–5. G. Linck, "Die Bildung der Oolithe und Rogensteine," *Jahrb. f. Min.*, 1874, pp. 495–513. A. Roth-

suffices for all. The spherical shape, it is agreed, is due to the particles having been rolled about by waves and currents during the precipitation of the lime, so that every side of a particle in turn received its share;[1] but opinions are not unanimous as to how the precipitation has taken place. Some hold that it may be due to inorganic means such as give rise to stalactites and tufa, while others refer it to organic agencies, such as the life-processes of algæ, some of which are certainly concerned with the precipitation of lime from solution. Some algæ actually build up a calcareous framework; others by their life-processes and by their decay after death, seem to have either a chemical or a catalytic effect that leads to precipitation of lime.[2]

The solubilitiy of calcium-carbonate is small in salt water, and decreases with increase of salinity and temperature. Hence it is not surprising to find that it is in the hotter regions of the earth and in shallow land-locked waters that the precipitation of ooliths takes place, e.g. along the shores of the Great Salt Lake [3] and of the Red Sea, and around the Grand Canary and other tropical islands.

Despite a conflict of interpretations it is reasonable to conclude that while calcareous ooliths originate in a variety of ways, yet *in the sea* they are at the present time only being formed in profusion in gently-agitated warm waters that are highly charged with lime-salts (i.e in tropical and subtropical regions); and that algæ are often instrumental in causing the precipitation of the calcium carbonate, though perhaps the material precipitated in some cases serves no functional purpose in their life, and may have a structure entirely independent of the organisms themselves.

Oolithic limestones are so characteristic of the Middle Jurassic of Britain that the name "the Oolites" has long been given to that part of the system. We may picture the environment in which they

pletz, "On the Formation of Oolite," *Amer. Geol.*, vol. x, 1892, pp. 279–82. Summary in A. W. Grabau, *P. of S.*, chaps. ix and xi, and W. H. Twenhofen, *A Treatise on Sedimentation*, pp. 534–43. E. B. Wethered, *Geol. Mag.*, 1889, p. 200.

[1] Similar oolitic structures occur in ironstones, and are attributable to the same cause, see p. 137.

[2] D. Mawson, "Some South Australian Algæ Limestones in Process of Formation," *Proc. Geol. Soc.*, 1929, p. 70.

[3] In the Great Salt Lake of Utah we find an association of ooliths and algæ, and it has been claimed by some that the algæ have actually built up the ooliths. The same may have been the case in the Jurassic pisoliths that display the ramifying tubules referred to above. Linck, on the other hand, denies that algæ have anything to do with the precipitation of the calcium carbonate, which he claims on experimental grounds to have proved must take place when calcareous solutions reach the concentrations that are found in the waters where ooliths are being formed. He regards the algæ as merely coating over the chemical precipitates and later becoming enclosed by further deposits of lime.

originated as having been similar to that found in the shallow tropical seas and in coral-reef lagoons of to-day, for the profusion of fossils and the absence of detrital matter suggest that they came into being under a warm climate in shallow clear water on a sea-floor carpeted by white sand and mud, ever-shifting oolith-grains, broken shells and lumps of dead coral, and inhabited by a host of living organisms, amongst which algæ played an important but inconspicuous part, as they do in the modern coral-reef. In some oolites the abundance of fossils and their partially rolled or corroded state fits in with this *in situ* conception of their formation; but there are others in which a false-bedding is visible that indicates that they at least were built up of ooliths drifted by water or by wind [1] to their present position.

Shelly limestones also abound in the Middle Jurassic. In them are whole and broken shells of molluscs and brachiopods, sea-urchins, crinoids, and other shallow-water organisms. These limestones are comparable in origin to the shell-sands that floor many shallow seas at the present time. Such deposits are essentially neritic. In the Jurassic they sometimes pass laterally into oolites, or occasionally into *coral-limestones*. In the latter the coral skeletons (*Isastrea*, *Thamnastrea*, etc.) build up a large part of the rock, though there is always an abundance of other fossils. True coral-reef deposits are rare in the Middle Jurassic though found in the Corallian formation (p. 150).

[1] Deposition of oolites by wind is now occurring on the shores of Florida, the Great Salt Lake, Red Sea, etc. (W. H. Twenhofen, *op. cit.*, p. 539).

CHAPTER XIII

THE UPPER JURASSIC ROCKS

The classification adopted here (see p. 129) is:

5.	*Purbeckian* . .	Freshwater limestone with marine intercalations.
4.	*Portlandian* . .	Marine sands and limestones.
3.	*Kimmeridgian* .	Blue clays and shales, sometimes bituminous (marine).
2.	*Corallian* . .	Coral and shelly limestones in the south-west and in Cleveland (North Yorks.), but blue clay from Buckinghamshire to South Yorks. (marine).
1.	*Oxfordian* . .	Blue clays with sandy limestones at base (marine).

It will be seen from the above classification that, with the exception of the estuarine beds of the Purbeckian, the whole of the Upper Jurassic of England is a marine formation. So it is also in Scotland, as far as can be judged from the very small remnants of the lower three stages which alone are preserved.

General Physiography.—It is convenient to treat the Oxfordian, Corallian and Kimmeridgian together.

In the *Oxfordian*, though the distribution of land and sea was not very different from that prevailing in middle Jurassic times, yet there was an expansion and deepening of the sea; for *blue-mud* conditions (pp. 53–4) resembling those of the Lias extended throughout England and into Northern Scotland (Fig. 61*a*). A great bathyal clay-series resulted, in which Ammonites and Belemnites abound. In England the dominant factor influencing deposition was a renewal of uplift in South Yorkshire (Market Weighton Axis). Here non-deposition and contemporary erosion reduced the Oxford clay from its normal thickness of 500 to about 120 feet (Fig. 61*a*, M.W.).

In the *Corallian* there is the record of a brief return, both in North Yorkshire and in the south and west of England, to clear shallow seas with corals, brachiopods, and sea-urchins, abounding under conditions resembling those found in modern coral-reefs and in the clear seas adjacent to them. Shells and tests, both whole and

comminuted, are mingled with ooliths to build up the Corallian limestones, some of which are true coral-reef deposits. Arkell has shown [1] how certain shells are found almost exclusively in the coral-limestones, a feature that is characteristic of modern reefs, as it was of the Carboniferous reefs so many ages before (pp. 316–7).

In the counties of Buckingham, Bedford, Huntingdon, Lincoln, and part of Yorkshire, however, the Ampthill Clay replaces the

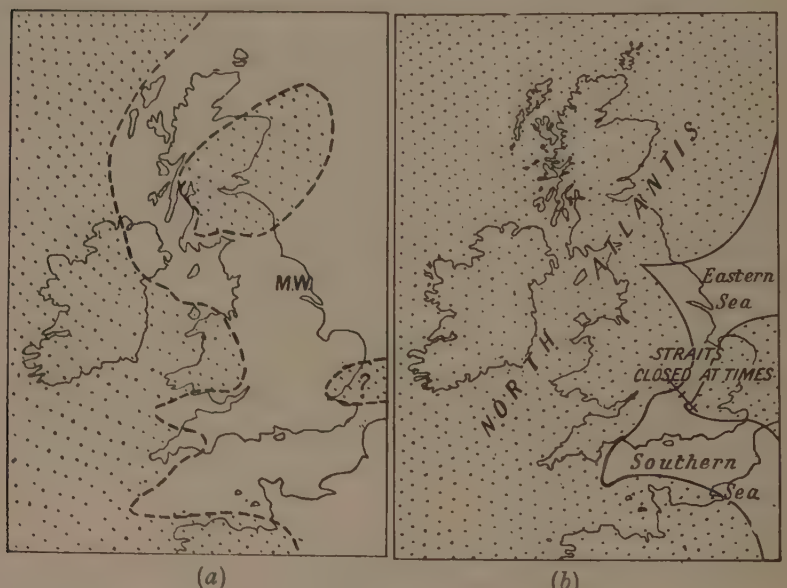


FIG. 61.

(*a*) Oxfordian Geography. Land stippled. M.W., Market-Weighton axis of uplift. (*b*) Portlandian Geography. Land stippled, crossed line axis of uplift. Based on Jukes-Browne and Stamp.

limestone, and the reef-building fossils disappear, the muddy bottom having doubtless been inimical to their growth. A diminutive reef is, however, seen at Upware in Cambridgeshire in the midst of the clay-facies. Here a typical coralline limestone and a typical fauna is found over a few acres, while the Ampthill Clay surrounds the reef on all sides, so far as is known. Conditions favouring reef-formation existed, however, at this time not only in England but widely over the Continent, as is shown by the distribution of Corallian limestones indicated on Fig. 62.

[1] W. J. Arkell, "Aspects of the Ecology of certain Fossil Coral-reefs," *Journ. of Ecology*, vol. xvi, 1928, pp. 134–49.

The Corallian was an interlude; for the *Kimmeridgian* is everywhere a shale formation, representing a return to muddy bottoms similar to those of the Oxfordian and Lias.[1] Back came the Ammonites and Belemnites, and mud-loving lamellibranchs! Gone are the corals, sea urchins and brachiopods! So great was the amount of decayed vegetable and animal matter at times that highly bituminous clays and oil-shales were formed. As in the Lias, the calcareous matter is represented by cement-stones, perhaps of secondary origin (see p. 136).

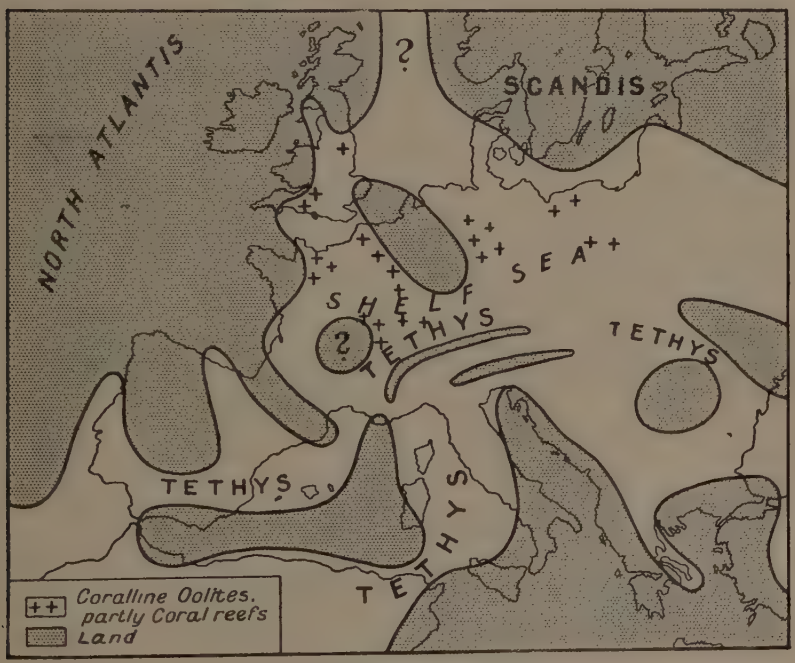


FIG. 62.—Europe in Corallian times.
Land stippled. Based on Haug and Arldt.

The variations in thickness in these three formations are shown on the section, Fig. 53. The remarkable attenuation of the Oxfordian in South Yorkshire has already been commented on. From Corallian times onwards, a gradual uplift occurred across Bucking-

[1] W. W. Watts has suggested that the alternation of muddy and clear seas indicated by the recurrent alternations of clays and limestones in the Middle and Upper Jurassic may be connected with periodic changes of climate (*Proc. Geol. Soc.*, vol. lxvii, 1911, p. lxxxiii).

hamshire and Bedfordshire, but on a much less noticeable scale than in South Yorkshire. Elsewhere subsidence was proceeding, and attained a high value in Dorset: as is evidenced by the fact that the Kimmeridge Clay there attains a thickness of 1,000 feet. Traced northwards it becomes thinner over the Midlands, but expands again in Lincolnshire and North Yorkshire. It has, however, been removed by pre-Cretaceous erosion over the Market Weighton anticline, so that it is impossible to say what effect that structure had on it. It is probable, however, that thinning took place here as in the earlier stages.

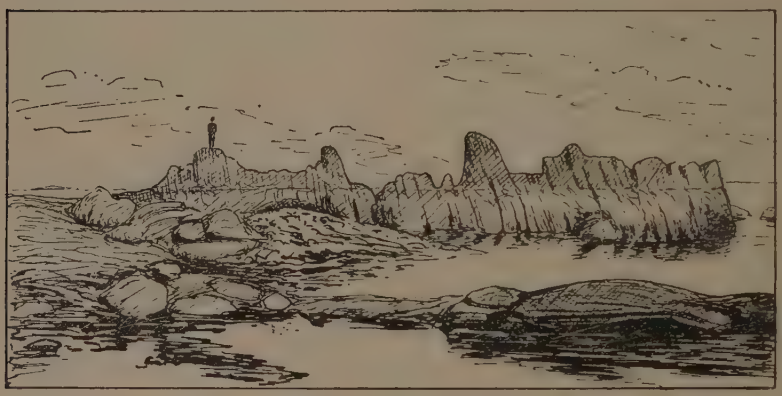


FIG. 63.—The "Fallen Stack" in the Kimmeridgian Boulder Beds; other boulders in the foreground. Portgower, Helmsdale, Caithness.

Dimensions of stack: 150 feet long, 90 feet in width, and 30 feet in height, as it lies with the bedding vertical. (After a photo by the Geological Survey.)

In Sutherland in the north-east of Scotland great boulder-beds of Kimmeridgian age are found. In many cases the boulders are cemented by a calcareous matrix and sometimes they lie interbedded with dark shales. The blocks are all made of Old Red Sandstone and have been interpreted [1] as the cliff-talus and boulders of a rock-bound coast with cliffs and sea-stacks carved from that formation. The most interesting feature is a great mass of sandstone which lies in the shales with its bedding upturned (Fig. 63). It represents a sea-stack at least 150 feet high that fell, undercut by the Kimmeridgian waves, just as might happen to-day on the Caithness coast a few miles away (Fig. 64).

[1] M. MacGregor, *Trans. Geol. Soc., Glasgow*, vol. xvi, 1916, pp. 75–84. See also "Geol. of the Country round Golspie," *Mem. Geol. Surv., Scotland*, 1925, p. 107. E. B. Bailey and others, *Journ. Geol.*, vol. xxvi, 1928, pp. 577–614.

In *Portlandian* times great changes took place in the distribution of land and water. Over the British Isles the sea retreated so far that it was probably confined to two areas in England: one over Lincolnshire, Yorkshire, and adjoining districts; the other over the southern counties (Fig. 61*b*). Owing to the overstep of the Lower

FIG. 64.—Sea-cliffs and stack of Old Red Sandstone. Coast of Caithness. (After a photo by the Geological Survey.)

Cretaceous in Yorkshire and to Pre-Cretaceous erosion, our knowledge of the Portlandian beds north of the Midlands is based on a few derived fossils found in the Lower Cretaceous rocks (p. 160). These fossils are rather distinctive, and suggest that the Midlands then formed an isthmus, or at any rate a barrier, between this *Northern* sea and the sea which overspread the southern counties, and which may therefore be termed the *Southern Sea*. It is possible that the

barrier was at times broken by a strait that temporarily allowed the waters to mingle.

In the Southern area the presence of normal marine sands and oolitic limestones, including the famous Portland Building Stone, denote a return to shallow water and clear seas after the muddy conditions of Kimmeridgian times. The Ammonites in the Portlandian attain an enormous size, being frequently two feet or more across.

In *Purbeckian* times the retreat of the sea had proceeded so far that all Britain was land,[1] save an area in the south approximately the same size and shape as the southern Portlandian sea. Here freshwater beds with marine intercalations are found, showing that estuarine or deltaic conditions prevailed, the region sometimes being under the sea and sometimes forming a great delta. Subsidence went on apace in the south, for the Purbeck Beds, which in Buckinghamshire are but a few feet thick, reach 400 feet in the Isle of Purbeck and in Sussex.

As will be shown in the sequel, there was no break in the sedimentation between the Purbeck Beds and the succeeding freshwater Wealden Formation (Lower Cretaceous). The subsidence in the south was also continued throughout the Wealden period (see p. 162).

The Estuarine or Delta-facies of the Purbeckian.—The Purbeckian where typically developed in the "Isle of Purbeck" in Dorset, presents an interesting series of strata, some marine, some terrestrial, but the major part freshwater and estuarine. The terrestrial deposits, known as "dirt-beds," consist of dark earthy material, sometimes gravelly. They represent ancient soils. In some cases on the dirt-bed rest the stumps of conifers with their roots embedded in the soil, the trees having been broken off at a height of about 3 feet. Among the stumps there are many prostrate trunks up to 20 feet in length and with a diameter of 2 feet or more. The trunks are enveloped in limestone having the characteristics of tufa, such as is thrown down in water supersaturated with carbonate of lime. The tufa passes laterally into freshwater limestone composed of the shells of a small bivalve crustacean, called *Cypris*. It is therefore probable that the trees became submerged in a lake, and formed nuclei for the precipitation of the tufa, and that the water was infested by such countless myriads of *Cypris* that a deposit practically consisting of their shells came to occupy the intervening area (Fig. 65). Other earthy beds are full of the bones of turtles and fish, and have yielded teeth and bones of a few small primitive herbivorous and insectivorous land-animals

[1] Some authors maintain that the lowest part of the marine Speeton clays of Yorkshire is of Purbeckian age, but the fossil evidence is not conclusive.

which are of particular interest as early forerunners of the warm-blooded mammals. Yet other beds abound in the wing-cases of insects on which the latter animals subsisted.

The estuarine and freshwater beds are partly clays and partly limestones. As is usual in freshwater limestones, they are each largely built up of innumerable shells of one or two species, usually of molluscs and occasionally of crustaceans, as in the Cyprid-limestone just referred to. The most famous of the rock-types is the so-called "Purbeck marble," really a dark limestone made almost exclusively of the water-snail *Paludina*. Brackish-water shells, such as *Cyrena* and *Hyrobia*, are common in other limestones, and indicate estuarine conditions.

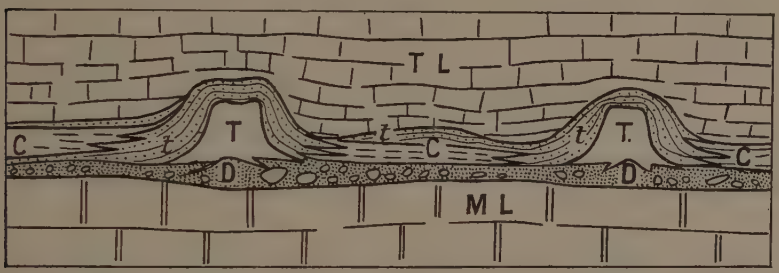


FIG. 65.—Diagram-section to illustrate the occurrence of the Purbeckian "Fossil Forest" at Lulworth.

T.L., thin-bedded limestone; t, tufaceous limestone; C, Cyprid-limestone; T, tree trunks, often silicified; D, "Dirt Bed"; M.L., Fairly massive limestone.

The marine incursions are chiefly recorded in limestones of different types. One of these, some 5 or 6 feet thick, is known from its rough porous appearance as the "*Cinder-bed*," and consists exclusively of oyster shells. This is evidently a fossil oyster-bed.

The typical Purbeckian area therefore provides a record of a district that sank gradually, but not uniformly. It was never far above or below the level of the sea, so that a small displacement was sufficient to produce considerable geographical changes; a land-delta at times, at other times an estuary or an arm of the sea, occupying the site.[1]

The Life of the Jurassic.—The foregoing sketch of the events of Jurassic time in Britain would be incomplete without some further reference to the life of the period. Mention has already been made of the service the Ammonites and Belemnites render as time-indices (pp. 62, 140). But apart from these, the

[1] A. Strahan, "Guide to Geol. Model of the Isle of Purbeck," *Mem. Geol. Surv.*, 1906.

Jurassic seas swarmed with brachiopods, corals, lamellibranchs, gastropods, crustaceans, and sea-urchins. The study of these in various parts of the earth has revealed differences that are held by some to indicate zoological provinces in the Jurassic seas comparable with those of to-day.

Though the common invertebrate marine animals are the most valuable for correlation-purposes, and as such usually receive the fullest treatment, the vertebrate animals are of more general interest. The ganoids were still the dominant class of fishes, and their glistening enamelled scales and teeth are most attractive fossils. The period was one during which the reptiles attained a great diversity of type and, in some cases, enormous size. To a large extent they were adapted to the various habitats that are now filled by mammals and birds having similar special adaptations. In the Lias, for instance, the swimming reptiles, *Ichthyosaurus* and *Plesiosaurus*, resembled the whales and porpoises amongst recent mammals, in having swimming paddles instead of normal limbs, and in possessing, like some whales, a formidable array of spiked teeth for catching fish. On the land there were carnivorous and herbivorous reptiles, while others were as much at home in the marshes and swamps as the hippopotamus and rhinoceros of to-day. Flying reptiles are also known (Pterodactyls). These are comparable with the bats in that a skinny membrane was stretched from the elongated and lightly-built bones of the forearm, wrist and fingers to form a wing. The most perfect examples of Pterodactyls come from the very fine-textured limestones of Solenhofen in Central Bavaria. The same rock has also yielded the greatest marvel among fossils, *Archæopterix*, the earliest-known bird. Resembling the Reptilian Pterodactyls in having a toothed beak and in other anatomical details, this creature had real feathers, though those of the tail were arranged on either side of the posterior vertebræ much as the individual barbs are placed on the axis of a feather in a recent bird.

The mammals which first appear in the Rhætic of Britain were, during the Jurassic, still small and insignificant animals, of which we know hardly anything (p. 154), except that their teeth betray them as mainly subsisting on insects, of whose presence there is abundant evidence throughout the period.

The Estuarine Beds of the Lower Oolites and the Purbeck strata give us an insight into the plant life. The most important plants are usually referred to the *Cycads*. Cycads form at the present day a minor part of the flora of some of the warmer regions of the world, but differ widely from their Jurassic relatives in their reproductive parts. In addition to these, *Equisetites* was in places a dominant form. This plant is an ancestor of the horse-tails (*Equise-*

tum) and not distantly related to *Calamites* of the Coal Measures. *Araucarian conifers*, a stock from which trees like the "Monkey Puzzle" sprang, are also known to have abounded, and *Ferns* constituted an important element in the flora. Quite recently Dr. Hamshaw Thomas has found in Yorkshire a new group of Angiospermous plants, i.e. flowering plants, to which he gives the name *Caytoniales*. If these are really Angiosperms, they are the earliest known members of the Class that now forms the dominant type of plant.[1]

[1] H. Hamshaw Thomas, *Phil. Trans. Roy. Soc., London*, Sec. B, vol. ccxiii, 1925, pp. 299–363.

CHAPTER XIV

THE CRETACEOUS ROCKS

At the end of Jurassic times, as we have just seen, p. 154, a great deal of Britain became land; and this fact has been made a reason for separating off the next-formed strata as the Cretaceous System. From the present point of view, however, we may treat the Cretaceous formations as recording a continuation of epeiric conditions; for they were deposited partly in a lake and partly in a shallow sea that gradually overspread most of England and, deepening in Chalk times, submerged parts of Ireland and Scotland as well.

We have therefore in the Cretaceous strata below the Chalk a record of a great transgression, while the Chalk itself chronicles the conditions on a sea-floor that remained remarkably unaltered during a great length of time.

The present chapter is devoted to the control which these Cretaceous environments exerted on the processes of deposition.

Distribution.—Cretaceous rocks underlie much of Eastern, South-Eastern, and Southern England. They also occur in Northern Ireland and the west of Scotland. The Lower Cretaceous has a much more limited extent and exhibits a more varied series of facies than does the upper division of the system. In the latter the Chalk, from which the system derives its name (Latin: *creta*, chalk), is the principal formation. It possesses a remarkable uniformity of lithology, not only in England, but in Ireland, Scotland, France, Denmark, and Russia.

Structure—The outcrop of the Cretaceous runs from Yorkshire, south-west to Dorset; and Eastern and Southern England is floored by the formation, save where Cainozoic rocks still cover the Cretaceous in East Anglia and the Thames Valley, and in Hampshire, Dorest, and the Isle of Wight. These are synclinal areas in which the newer rocks have been preserved. In general, therefore, the arrangement of the strata may be said to consist of south-easterly dipping sheets that are affected by obliquely transverse

east-west up- and down-folds. Of these the synclines or basins of London and Hampshire are separated by the anticlinal dome of

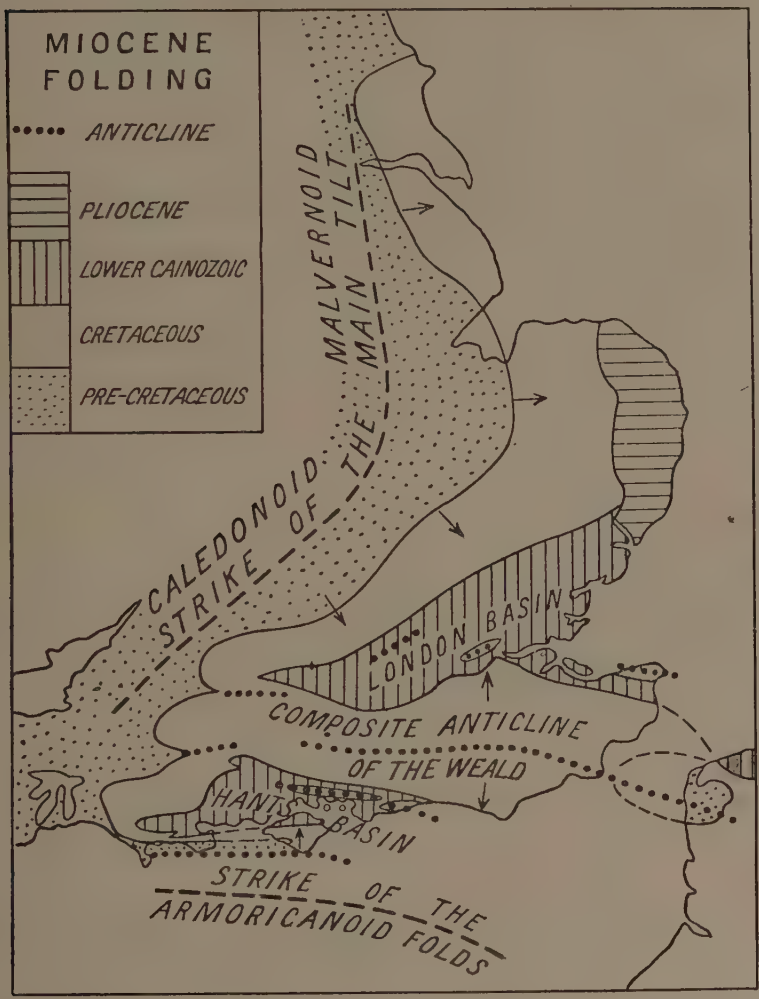


FIG. 66.—Distribution of Cretaceous and Cainozoic Rocks in S.E. England, and the principal fold-axes of Miocene Age.

the Weald and its continuation westwards; and the Hampshire basin is bounded on the extreme south by the monoclinal up-folds of the Isles of Wight and Purbeck (Figs. 66, 67).

Classification.—The Cretaceous is susceptible of division as follows:

Time-epochs.	Southern Area.	Northern Area.
Upper Cretaceous		
Danian, Maestrichian	Absent	Absent
Campanian, Senonian	Upper Chalk	Upper Chalk
Turonian	Middle Chalk	Middle Chalk
Cenomanian	Lower Chalk	Lower Chalk
Albian or Selbornian	Upper Greensand and Gault Clay	Red Chalk
Lower Cretaceous		
Vectian	Lower Greensand	Speeton Clay of Yorks, and Tealby, Claxby, and Spilsby Beds of Lincolnshire.
Neocomian	Wealden Beds	

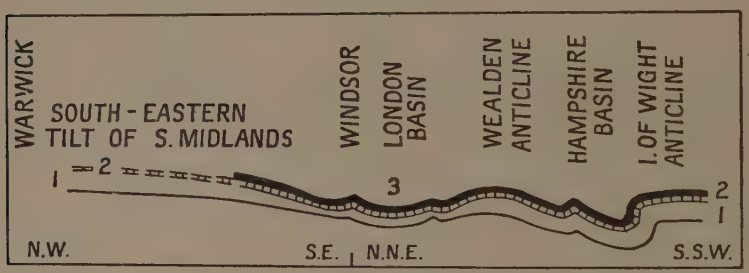


FIG. 67.—Diagram-section from Warwick, S.E. to Windsor, thence S.S.W. to Isle of Wight; to show the folding.

1, Jurassic and Lower Cretaceous; 2, Upper Cretaceous; 3, Tertiary. Present surface not indicated.

Geography of Lower Cretaceous Times.—At the end of the Jurassic period, sedimentation had probably been restricted (see p. 154) in England to two areas, separated by a sort of isthmus extending west or north-west from that part of the Eastern or Anglo-Belgian Massif (p. 82) which underlies the Thames Valley (Fig. 68*a*). To the north, in Lincolnshire and Yorkshire, the dawn of the Cretaceous saw a sea that spread eastwards to Germany. Here were deposited marine clays and sands that more or less bridge over the passage from Jurassic to Cretaceous times (Speeton Series of Yorks and the Spilsby and Claxby

Beds of Lincs). This sea persisted throughout the Lower Cretaceous period.

Very different were the conditions to the south of the isthmus. In Neocomian times a great lake covered the region to the south of the Vale of Wardour as far west as Dorset, and extended across the Weald of Kent into the north of France and Belgium. In it were laid down as the delta of a great river the mighty pile of fresh-water sands and clays which are known as the Wealden Formation. The fossils declare the country to have been covered by luxuriant vegetation and peopled by a varied fauna.

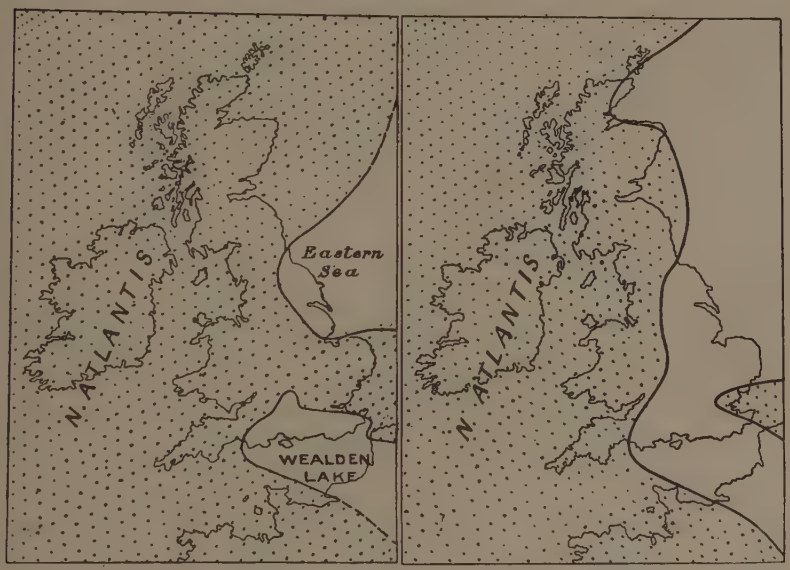


FIG. 68.—(*a*) Neocomian Geography. (*b*) Vectian Geography. Land stippled.

In Vectian times the sea invaded this area from the south.[1] The first deposits to be formed were the marine Atherfield Clays. Later, sands, in part ferruginous, in part glauconitic, were deposited (the Lower Greensand) over much the same region; but at times the waters of the sea advanced northwards on to the isthmus, and may

[1] Tethys persisted throughout Cretaceous times, and the seas that overspread France and South England were in connection with its waters. The rocks deposited in Tethys, and their contained fossils, are, however, distinctive, and show that its waters belonged to a different zoological province.

have even been joined temporarily to those of the northern sea (Fig. 68*b*). But, for the most part, the latter remained separate. The effect of this is seen in the northern fossils, which are not so closely related to South-of-England Vectian types as with forms found in contemporary deposits in Hanover and Russia. The two English facies are therefore distinct on account of the fauna having belonged to two provinces separated, perhaps, by an isthmus, as in the case of the Red Sea and the Mediterranean at the present day.

As a result of the geographical conditions just outlined, it is found that in the southern region both the Wealden and the Lower Greensand deposits form huge wedge-shaped lenses of sediment which, thickest in the Weald of Kent, thin rapidly when traced towards the north (Fig. 52). Since the rocks, without exception, are shallow-water in origin, it is clear that a slow but continuous downward movement must have affected the crust in the south, whilst the Midlands and the Eastern Massif remained almost stationary. Further reference is made to this phenomenon in the sequel (p. 168).

Geography of the Upper Cretaceous Times.—The conditions just outlined obtained during Lower Cretaceous times, but in the second part of the period a general submergence carried the sea right across the isthmus, and greatly diminished the area of the surrounding lands. The isthmus, however, continued to influence the deposition of sediment, for in the south the Albian is predominantly a thick blue or grey clay-formation known as the Gault which passes locally upwards and also, in Dorset, laterally into glauconitic sandstones. But the 200–300 feet of Albian sediment in Southern England dwindles northwards, and is represented in Lincolnshire and Yorkshire by a few feet only of marl and sandy red chalk. In the Eastern Midlands also the Gault has in places suffered severe contemporaneous erosion, so that only parts of the sequence are preserved. Again, the so-called Cambridge Greensand in the Cambridge district overlies the eroded upper surface of the Gault, and contains phosphatic nodules and fossils derived from that formation. These features point to the intermittent nature of the subsidence in the Eastern Midlands and East Anglia, the erosion by waves and currents at times preventing the accumulation of sediment or accomplishing the removal of that which had already been deposited.

The glauconitic sands at the top of the Gault in South-East England extend westwards farther than any other Cretaceous rocks, and directly overlie Triassic and older strata in Devon (Fig. 69). This feature and the presence of still later Cretaceous rocks in Ireland and Western Scotland indicate a great extension of the sea,

which is known as the "*Cenomanian transgression.*" [1] The term transgression is used to imply a widespread submergence which results in the deposition of new strata far and wide over an eroded surface of more ancient rocks. This can only take place when the land bordering the sea has been reduced to plains. The possible causes of such submergence are discussed on p. 8.

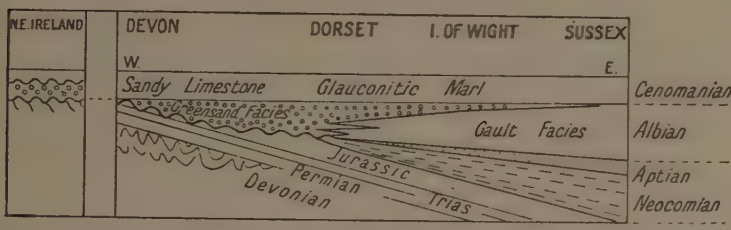


FIG. 69.—Diagram to illustrate the relationship between the Greensand and Gault Clay facies of the Albian; and to show that the Greensand facies (with *Pecten asper*) in Ireland is Cenomanian in age.

Wavy line, the unconformity of the "Cenomanian Transgression." Not to scale.

The Cenomanian transgression can be traced over a large part of Europe, though it commenced and reached its maximum at varying times in different regions. Thus, whereas in Southern England submergence began in the Vectian and continued westwards in the Albian epochs, the sea was still encroaching on the land in Ireland, Scotland, and France, as late as Cenomanian times.

The Greensand Facies.—The neritic deposits laid down as the Upper Cretaceous sea advanced, have a distinctive lithology. They are sands, typically of a green colour which is imparted by grains of the mineral glauconite. The presence of this mineral is usually held to denote slow accumulation of sediment such as occurs in seas into which few rivers drain or in which but little terrigenous detritus settles on account of tides or currents. A deficiency of organic matter also appears to be a controlling factor.[2] Such glauconitic sandy or clayey bottoms are known from many parts of the ocean-floor at the present day. Sometimes the sands are "iron-shot" and contain ooliths of limonite, the formation of which has been shown above (p. 138) to be consistent with a sea-floor deficient in terrigenous detritus.

Certain fossils, such as *Pecten asper* and *Exogyra conica*, so commonly characterize the "Upper Greensand" that the latter is often spoken of as the zone of *Pecten asper*. The fossils are,

[1] Termed Cenomanian because in many parts of the Continent the maximum extension of the sea was reached in Cenomanian times.

[2] L. W. Collet, *Les Dépôts Marins*, 1908, pp. 51–2.

however, facies-fossils (p. 61), and the rocks vary considerably in age in different places. Thus in the south-east of England the "Upper Greensand" caps the Gault with *Ammonites* (*Schloenbachia*) *rostratus*, and is of Albian (Selbornian age), but in Devon the greensands with *P. asper* are of the age of the Lower Chalk of South-East England, though a sandy coastal facies of the *A. rostratus* beds is also found. In Ireland and Scotland the greensand facies is of a still later date, the fossils showing that the shallow sea had not reached those areas until Cenomanian times (Fig. 69). The name "*Pecten asper* zone" is therefore a misnomer, because the sediments characterized by that fossil and its associates do not represent the deposits of a given epoch of time, except in a very broad way; and in detail there is a great divergence between the lithological and chronological classification. This is another example of diachronism (p. 140).

The Chalk.—It was not only in the British Isles that the sea in Albian and Cenomanian times advanced on to the land. The same thing happened throughout Western and Central Europe. The muddy and sandy glauconitic sediments that mark the actual advance, with its shallow-water or neritic phase, give place upwards to the extraordinarily uniform and pure limestones of the Chalk which represent a bathyal phase. This deposit shows but little variation throughout its extent from Ireland and the west of Scotland, through England, Northern France, Westphalia, Denmark, Sweden, into Central and Southern Russia (Fig. 70). Though the Chalk contains abundant foraminifera, and in many respects is comparable to abyssal oceanic oozes, such as are now accumulating at great depths in the Atlantic Ocean and elsewhere, its other fossils show it to be of comparatively shallow-water origin.[1] A large proportion of the matrix of the Chalk is everywhere amorphous, and this has been claimed to be a chemical precipitate such as is forming on the Bahama Banks at the present day.[2]

The absence of terrigenous detritus and the extreme purity[3] of the limestone are explicable, when it is recollected that the Chalk sea covered so much of the former land-areas that these, already reduced by long-continued denudation to a low peneplain, could

[1] Kendall, however, argues for accumulation at a depth of over 9,000 feet on account of the absence in the Chalk of remains of animals whose shells were aragonite. He states that this was due to their solution as they fell through the great depth of water. In the present-day oceans such solution is only complete at depths exceeding 9,000 feet. See Kendall and Wroot, *G. of Y.*, p. 370, for a full discussion of the depth of the Chalk Sea.

[2] W. A. Tarr, *Geol. Mag.*, 1925, pp. 252–64. Useful discussion of precipitation of $CaCo_3$ in sea-water.

[3] This statement excludes the flint nodules which are everywhere very abundant in certain parts of the Chalk.

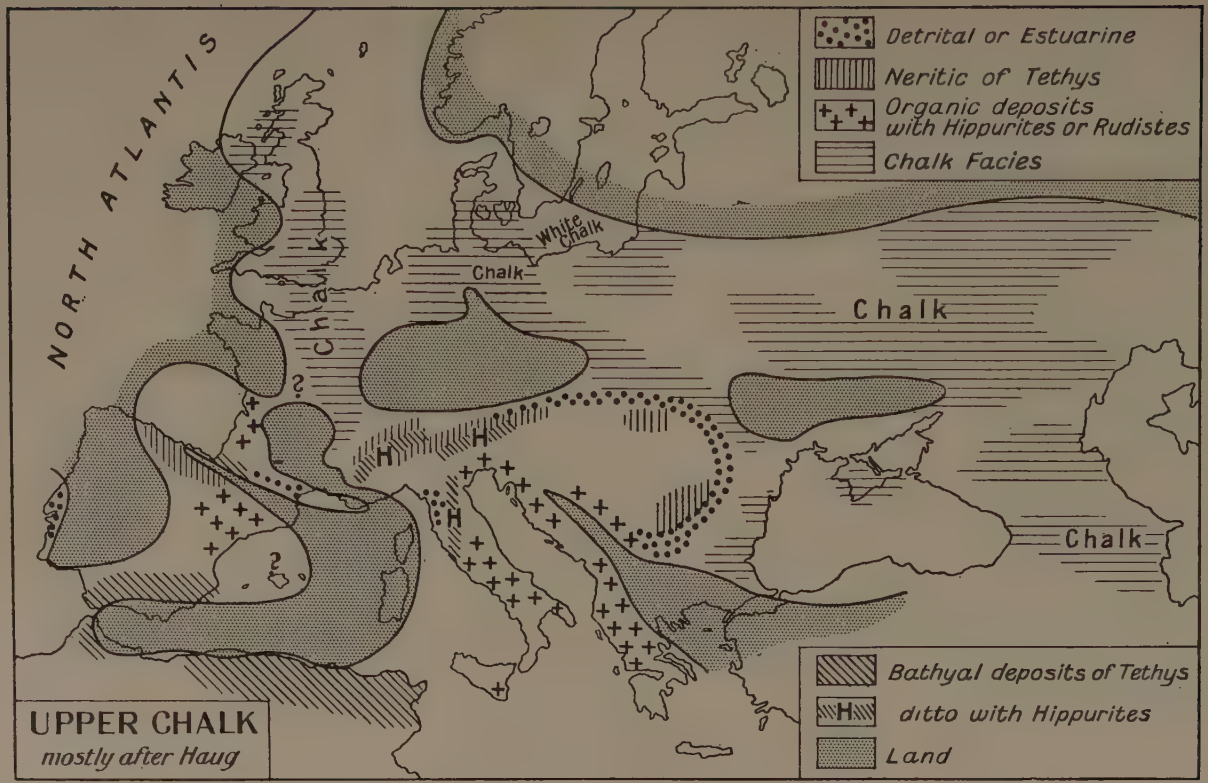


FIG. 70.—Europe in Upper Cretaceous times. Based on Haug.

send but little sediment into it. It has recently been suggested that the shores of the Chalk seas were riverless deserts.[1] If this concept be true, it supplies a further explanation of the general absence of terrigenous material. For these reasons the Chalk must be regarded as a clear-water, rather than an abyssal deposit. The enormous lateral extent of its individual rock-sheets is in strong contrast to the local nature of many of the Cretaceous formations so far described, and forces us to recognize the widespread and uniform nature of the epeirogenic depression that submerged so large a part of Central and Eastern Europe (Fig. 70). The Chalk is thus the culminating point of the Cenomanian Transgression.

The Continuity of Marine Evolution during Chalk Times.—The remarkable lithological uniformity of this great bathyal formation reflects a corresponding uniformity of conditions during the immense period of time occupied in its accumulation. As might be anticipated, the monotony of the lithology is accompanied by monotony in the type of organisms found as fossils. If evolution has gone on by the natural selection of continuously varying individuals, the Chalk should be an ideal formation in which to test the Darwinian theory of continuous evolution. Rarely can we find strata a thousand feet and more in thickness that have been formed under so constantly uniform an environment.

Dr. A. W. Rowe has examined the fossils of the Chalk from this point of view.[2] He and his collaborators collected enormous numbers of fossils from known positions in the formation, so that he could arrange them in the order in which they had existed in time. Confining his attention at first chiefly to the sea-urchins (Echinoids), he found that species which had formerly been regarded as distinct were in reality mutations (p. 59) or stages along a series of lineages, each of which varied gradually from the base to the summit of the formation. At any particular horizon each lineage was represented by forms that, in detail, differed from those occurring above or below (Fig. 71). Such mutations are valuable to the stratigrapher as zone indicators of a type that is especially reliable on account of the impossibility of their repetition during evolution; but the chief interest of his conclusions consists in the demonstration of the continuity of evolution, at any rate, in this case. Though possibly less well-established, a similar evolutionary sequence was afterwards claimed by Rowe and his collaborators to be demonstrable in other groups of animals whose remains are found in the Chalk.

The Mesozoic Cycle of Sedimentation.—Major cycles of erosion and of sedimentation are initiated in orocratic periods when

[1] E. B. Bailey, *Geol. Mag.*, 1924, pp. 102–16.
[2] A. W. Rowe, *Q.J.G.S.*, vol. lv, 1899, pp. 494–546.

new mountains and new lands come into being, but they are continued and finally completed during the age-long periods of relative stability and epeirogenic movements that follow. A sedimentary cycle may therefore begin with deposition in the hollows and around the shores of a new continent; but as the erosion of the land proceeds and epeirogenic movements supersede the orogenic ones, more and more of the land-surface is liable to be invaded by the sea. We may therefore expect to find continental deposits followed in upward sequence by littoral, neritic, and even bathyal sediments. Gradually

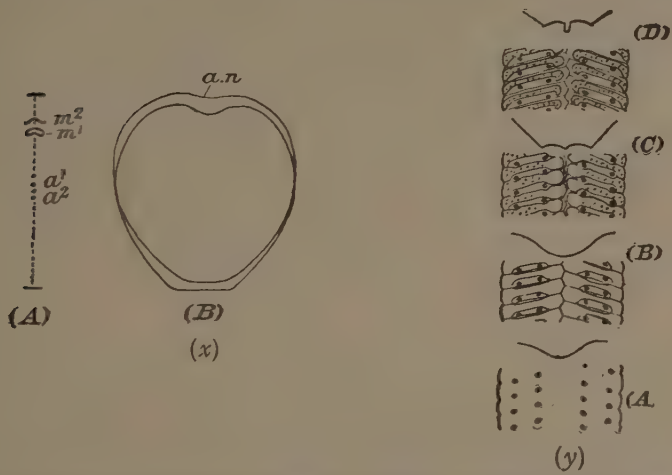


FIG. 71 *x* and *y*.—Evolutionary changes in *Micraster*. After H. H. Swinnerton.

	Low Zonal Type.	Fig.	High Zonal Type.
Length and breadth	Distinctly longer than broad (outer line)	71 (*x*) *B*	Length varies from slightly longer to slightly shorter than the breadth (inner line)
Position of apical disc	Well in front of centre (a^1)	71 (*x*) *A*	Central or only slightly in front of centre (a^2)
Depth of anterior notch (*a.n*)	Almost absent or at most only shallow	71 (*x*) *B*	Generally deep.
Position of mouth .	More distant from anterior border (m^1)	71 (*x*) *A*	Close to anterior border (m^2)
Character of the inner ends of ambulacral plates	Flat or slightly inflated, smooth surface (*A*, *B*)	71 (*y*)	Much inflated, granular surface (*C*, *D*)

a great pile of strata may be laid down on the now deeply-buried continental surface, in readiness for the next set of earth-movements to transform into new mountains and lands, thus terminating the one cycle and ushering in a second.

The Cretaceous period saw the approaching termination of the Mesozoic cycle of sedimentation that began with the Altaid, and ended with the Alpine orogeny (p. 170). The fullest sequence of strata was deposited in the geosyncline of Tethys, and from them the Alps were constructed; but quite considerable thicknesses of rock were laid down in the various cuvettes on the more rigid part of the Hercynian continent to the north of the Alps. In our own country the Midlands retain the completest record of the early part of the cycle (Permian, Trias, and Jurassic), but the maximum development of the sediments belonging to its later portion (Jurassic, Cretaceous, and Lower Cainozoic) is to be found in the south of England, especially in the Wealden area. It is just this region that suffered the greatest upheaval during the Alpine orogeny.

Trias is known to exist locally under the Weald, and it is probable that the cycle of sedimentation began at that time with the deposition of material in a depression within the worn-down Armorican Mountains. All through the Jurassic, Cretaceous, and Lower Cainozoic periods deposits, occasionally bathyal, but more often neritic or even continental, accumulated in this cuvette, which covered much of the southern counties east of Dorset and south of the Thames. The floor of the cuvette kept on gradually, though no doubt intermittently, sagging; while, to the north, the Eastern Massif under the Thames Valley, to which reference has been repeatedly made, remained stable, or intermittently rose, so that at times it was covered by the sea, but often formed dry land. That the Wealden Cuvette was not a deep one that was eventually filled up, but a shallow one that gradually sagged, can be proved by finding at various horizons beds which must have originated at or near sea-level. Such are the oolites of the Bajocian, Bathonian, Corallian, Portlandian, and the estuarine and freshwater rocks of the Purbeckian, Wealden, Eocene and Oligocene. Thus it may be seen that at several different epochs the sedimentation-basin, never very deep, had been filled up practically to sea-level, and that the thickness of sediments is in fact a measure of the amount of subsidence. This can be estimated to have been some 5,500 feet, for the Cretaceous rocks in the centre of the Weald must have originally been at least 3,000 to 3,500 feet, while the Kimmeridge Clay alone in places is known to be 1,250 feet thick, and probably follows a great development of Lower and Middle Jurassic.[1]

[1] A. Strahan, Pres. Address Geol. Soc., *Proc. Geol. Soc.*, vol. lxix, 1913, pp. lxx–lxxxiii.

At times deposition took place across the old ridge to the north, but even then on a lesser scale. Uplift was here often renewed, and led to the partial or complete destruction of such deposits. Thus the Gault Clay lies directly on the Palæozoic floor below London, though 30 miles away, many hundreds of feet of Jurassic and Lower Cretaceous strata intervene (see Fig. 52). This combination of excessive deposition over the Weald with diminished sedimentation and actual erosion in the London area has led to the Mesozoic strata, individually and collectively, having the remarkable wedge-shaped constitution that has already been referred to (pp. 127, 162).

The differential sagging as between the Wealden geosyncline and the Eastern Massif ceased to be noticeable in Upper Cretaceous times and the deposition of the Chalk indicates that the whole country slowly subsided, the Chalk, itself a fairly shallow-water formation (see p. 164), attaining a thickness of over 1,500 feet. This great deposit almost completed the cycle of sedimentation; for after its formation uplift set in, and although Lower Cainozoic strata were laid down in South-East England, they are relatively unimportant and were quickly followed by the earth-movements of the Miocene which brought in a new cycle in the earlier part of which we appear to be living.

V. THE ALPINE OROGENY AND THE DEVELOPMENT OF THE PRESENT-DAY CONDITIONS IN WESTERN EUROPE

CHAPTER XV

GENERAL OUTLINE OF THE GEOGRAPHICAL CHANGES OF CAINOZOIC (TERTIARY) TIMES

The Cainozoic period saw the end of the Mesozoic geography and the birth of a new Europe and of a new Atlantic Ocean, more or less as we know them to-day. We see within it the shaping of a continent by the interaction of repeated earth-movements, both orogenic and epeirogenic, with stupendous denudation and dazzling changes of climate.[1] The period was an orocratic one, and much of its history is bound up with the growth of the Alps, or rather of the *Alpides* (Suess), which term embraces not only the European Alps, but the Caucasus, Himalayas, and other chains that sprang up at this time (Fig. 74). The repercussions of the Alpine orogeny were felt as epeirogenic movements in France and England. Volcanic activity in Ireland, in North-West Scotland, and as far away as Iceland was probably the outcome of the break-up of the ancient Atlantic continent (Atlantis) and the growth of the present ocean.[2] Yet it is not inconceivable that all these phenomena are the expression of a single great cosmic event, such as the melting of the sima as suggested by Joly (p. 7).

The Cainozoic is subdivided as follows:

Upper or Neogene .	Pleistocene or Quaternary. Pliocene. Miocene.
Lower or Palæogene.	Oligocene. Eocene.

In tracing out the history of the period it is well to bear in mind that in the Palæogene Europe retained its Mesozoic aspect (Fig. 72).

[1] Wegener considers that the climatic changes are related to migrations of the pole resulting from the drifting of the continents.

[2] J. W. Gregory, Pres. Address Geol. Soc., *Proc. Geol. Soc.*, vol. lxxxv, 1929, pp. lxviii–cxxii, and A. Harker and J. W. Evans, cited on pp. 207–8.

Thus, the southern ocean (Tethys) persisted and was the site of vast bathyal deposition. In this sea the embryos of the Alps were beginning to appear as festoons of islands. Central and Northern Europe

FIG. 72.—Western Europe in Eocene times; based mainly on Haug and Stamp.

were land, except for the Anglo-Parisian Cuvette which was flooded by a warm sea. Probably the North Atlantic Ocean did not then exist in anything like its present state, and it is fairly certain that

Ireland and Northern Britain were part of a land-mass connected with Iceland. This Brito-Icelandic Province was the scene of great vulcanicity from central-vent and fissure-vent volcanoes (Fig. 72).

In the middle of the period (Oligocene to Miocene) the main upheaval of the Alps took place, accompanied by the dwindling of Tethys and the establishment of the Atlantic Ocean as we know it. Movements of less magnitude affected France and the British Isles, and converted this region into a diversified land-surface, on which a new system of rivers came into being. The various agents of erosion

FIG. 73.—Europe at the beginning of Pliocene times (Diestian, Pontic, Sahelian and Anversian). Based mainly on Haug.

gradually reduced the upstanding parts until a general peneplain was produced in late Miocene times.

The great changes that had taken place since Palæogene times are obvious if we compare the maps, Figs. 72 and 73, the latter representing the distribution of land and water at the beginning of the Pliocene. At about this period the present North Sea came into existence, invading the peneplained continent from the north-east; while great in-sinkings and considerable transgressions of the sea took place at a slightly later date to the south of the Alps to form the present Mediterranean Sea.

The west of Europe had thus in the Pliocene received the basis of its present general configuration, but it had still to undergo many

vicissitudes in the shape of earth-movement, erosion, and climatic changes that gave it its final touches. The most striking of these changes were the glacial episodes of the Pleistocene (Quaternary) period in which vast ice-sheets overspread North-Western Europe.

For the present purpose the Cainozoic on the one hand offers a record of hypogene processes and changes involved in the growth of a mountain-chain and of a new continent; and on the other hand it illustrates the surface or epigene processes that have brought into being the present geography (using the term in its widest sense). It is therefore from these two view-points that we shall approach our study of the system. It will, however, be convenient to consider separately the records of five different regions, each of which throws light on particular phenomena (Figs. 72 and 90).

1. **The Alpine:** at the beginning of the period still part of the Mesozoic Mediterranean (Tethys), later the scene of the uprise of the Alpine Chain. Nummulite-limestones are the characteristic deposits of the open ocean; sandstones and conglomerates, known as Flysch and Molasse are those of the region between the continent and the nascent Alps. . . . Studied as an example of mountain-building (Chapter XVI).
2. **The Anglo-Parisian Cuvette** (of Eocene to Pliocene times) covering South-East England, North-Eastern France, Belgium, Holland, and part of the North Sea. Partly marine, and partly estuarine and lacustrine deposits occur here. . . . Studied mainly with a view to tectonics and to development of land-forms (Chapter XVIIA).
3. **The Brito-Icelandic Province** (Judd) covering Northern Ireland, the Western Islands of Scotland, and possibly stretching into Iceland. A volcanic region in Palæogene times in which the Cainozoic rocks are predominantly igneous. . . . Studied mainly as a region of terrestrial fissure- and lava-cone volcanoes (Chapters XVIIB and XXV).
4. **The British Glaciated Region** in Pleistocene times (Fig. 90). . . . Studied mainly for the record it presents of glacial phenomena, and of their effects on the configuration of the country (Chapter XVIII).
5. **The British Extra-glacial Region** in Pleistocene times (Fig. 90). . . . Studied with a view to (*a*) the influence of the glaciation and epeirogenic movements on the evolution of the present topography, and (*b*) the influence of the climatic changes on the flora and fauna, and on man (Chapter XIX).

CHAPTER XVI

CAINOZOIC SYSTEM (*cont.*): THE ALPINE REGION

The Alpine Geosyncline.—Repeated reference has already been made to the Mesozoic geosynclinal sea of Tethys, and to the great pile of sediments, many of them bathyal, that accumulated in it from Triassic times onwards until the end of Lower Tertiary times. Hercynian Europe lay to the north, and Hercynian Africa to the south (Figs. 72, 74). Each had a broad continental shelf

FIG. 74.—The region of the Alpine Orogen, redrawn from L. Kober, 1922. The continental blocks of Eurasia and Gondwanaland separated by the geosyncline of Tethys.

sloping down to the deeper parts of Tethys that lay between them. The sea appears to have covered an area that was far wider than the Alps, but more or less parallel to their trend. All across its floor sediment accumulated, the facies of the deposits varying with their location in reference to the distribution of land or sea, depth of water, festoons of islands, etc. (p. 184), but many of the deposits were bathyal, in accordance with their geosynclinal origin (p. 11).

The Tertiary or Alpine "earth-storm" caught this mighty lens of relatively unconsolidated and unindurated sediment, and threw it into waves that folded and thrust the strata, and piled them up in slices one on another (p. 181). Not only so, but the underlying Palæozoic and crystalline rocks, weakened by the high temperatures to which the downfolding of the geosyncline had subjected them, were involved in the movement, and forced into and over the Mesozoic and Tertiary.

Thus were heaped up the chains of the Alpides that, following the site of Tethys, can be traced through Europe and Asia (Fig. 28).

In the early stages of the uprise of the European Alps there was a region (foredeep) to the west and north of the present chain that at times held lakes and at other times arms of the sea. Here accumulated the molasse or nagelfluh, a thick deposit of conglomerates, sands, and muds derived from the denudation of the ranges far to the south. The present Molasse-land and southern part of the Jura Mountains (Fig. 75 and p. 177) roughly coincides with the extent of this Oligocene and Miocene foredeep of the Alpine region. As time went on, the southern part of the Molasse was involved in the movements and the foredeep ceased to exist. To a considerable extent the northern border of the Alps has overridden it.

The Architecture of a Folded Mountain-Chain.—The interpretation of the vast volume of data that has been collected on the origin and structure of the Alps is still in the controversial stage. Here we shall refer only to those features which seem generally agreed upon by the leading Alpine authorities. The reader is, however, reminded that their conclusions are based upon hypotheses, the validity of some of which has been questioned.[1] Nevertheless we may examine their interpretation of the tectonics in the hope that they may help to elucidate the structure of more ancient chains; for it is logical to imagine that the Caledonides (p. 71) and Altaides (p. 272) were built up on much the same principles [2] as governed the construction of the Alps, and that their uplift had analogous effects on the geography of the periods covered by their formation (Chapters VI, XXII, XXIII).

The larger Structures of the Swiss Alps (Fig. 75)

The *folded ranges* of the Alps terminate abruptly against a *foreland* (Suess) or *hardened mass* (Kober) (p. 179) in which comparatively thin Mesozoic strata of the epeiric type lie on a Hercynian platform of far older rocks that were indurated and compressed, and intruded by granites during the Altaid orogeny, and now are only seen at the surface in horsts such as the Central Plateau, the Vosges and the Schwarzwald.

[1] Especially F. Heritsch, *Grundlagen der Alpinen Tektonik*, 1922; and *Die Deckentheorie in den Alpen*, 1927, translated by P. G. H. Boswell, *The Nappe Theory in the Alps*, London, 1929.

[2] Speaking of the still older ranges of the Pre-Cambrian Complex of Anglesey (*Geol. of Anglesey*, vol. i, p. 388), Greenly states that "the dominant structure . . . is recumbent folding combined with which is thrusting on a large scale." This statement epitomizes the modern conception of Alpine tectonics.

FIG. 75.—Tectonic Map of the Alps.

1, Po Alluvium; 2, Post-Alpine Tertiary and Molasse; 3, Trias and Jurassic of Plateau-Jura; 4, Hercynian Horsts; 5, Chain-Jura and Sub-Alpine chains of Provence; 6, Autochthonous Helvetian Mesozoics; 7, Autochthonous Hercynian Massifs of Alps (I, Pelvoux; II, Belle Donne; III, Aiguilles Rouges; IV, Mont Blanc; V, Aar; VI, Gotthard); 8, Helvetian Nappes and Roots; 9 and 10, Pennine Nappes (10, Dent Blanche Nappe and Roots; E, Engadine Window; T, Hohe Tauern Window); 11, Grisonid Mesozoics, K, Klippe of same; 12, Grisonid Crystallines; 13, Tirolids; 14, Dinarids; 15, Post-Alpine Massifs (Plutonic intrusions); 16, Post-Alpine volcanics. Based on Staub and Kober.

The Foreland comprises:

(1) A region to the north of the Alps and Jura Mountains known to geologists as the **Tafel-Jura** or **Plateau-Jura**, characterized by gentle warping (Plate I, A). In places powerful tensional movement has led to the horst and rift-valley structure, as in the Rhine Valley graben between the Vosges and Schwarzwald horsts (Figs. 4, 5 and 75).

(2) To the south and south-west of the Tafel-Jura lie the **Ketten Jura** (**Chain Jura**), in which the Mesozoic strata have been crumpled,

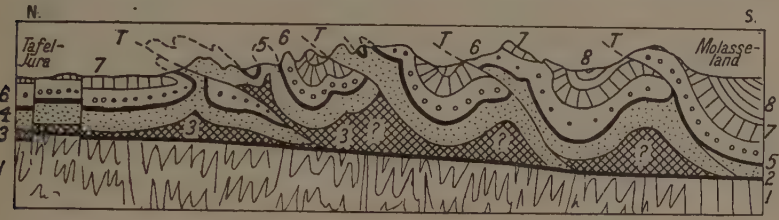


FIG. 76.—Diagram-section across the north-eastern part of the Jura Mountains; based on Buxtorf.

1, Hercynian Platform; 2, Permian, Bunter and Lower Muschelkalk; 3, Anhydrite Group (Mid-Muschelkalk); 4, Upper Muschelkalk and Keuper; 5, Lias; 6, Middle Jurassic; 7, Upper Jurassic; 8, Tertiary; T, Thrust.

overfolded and broken by overthrusts, whereas the Hercynian platform is believed to be barely affected by the Alpine movements, an arrangement involving the forward movement of the folded Mesozoic strata across the ancient platform (Fig. 76). This phenomenon is termed *décollement* and is a variety of disharmonic folding, that is to say folding which affects adjacent competent and incompetent rocks in different ways. The mountain ranges in the Jura coincide as a rule with the upfolds, and the valleys with the downfolds, of a series of earth-ripples induced by the thrust of the greater mountain-building forces to the south.[1]

(3) The lowland of the lake district of Switzerland. This is called the **Molasse-land**, and is structurally a great downfold between the Alps and the Juras (Fig. 75 and Plate I, A). During the uprise of the mountains this was the site of the "foredeep" (p. 175) covered at times by the sea, at times by lakes, that received the products of the erosion of the mountains, mostly gravel and sand, that now form the massive conglomerates of the "Nagelfluh" or "Molasse." The Ketten-Jura and the Molasse-land being the parts of the foreland nearest to the Alps, it is not surprising to find that they have a structure which is intimately connected with that of the main range, and which

[1] See, however, A. J. Bull, *P.G.A.*, vol. xl, 1929, p. 110.

is clearly due to the same causes. Thus the Jura, looked at broadly, is a complex crustal upfold, and the Molasse-land a fairly simple downfold, and both exhibit the arcuate form that appears to characterize the main chain on both a large and small scale. Thus the curving sweep of the Swiss Alps is repeated in the long line of mountains from Vienna, through the Carpathians and Transylvanian Alps to the Iron Gates on the Danube. Similar arcs may be detected in many folded ranges. On a smaller scale the phenomenon reappears in the short arcs into which the greater ones can be divided. In all cases the convex side of the curve is the one towards which the rock-sheets (p. 182) forming the mountains have travelled at the surface. Their advance was at places held up by obstacles, at other places it progressed more freely. The freer advance into areas of less resistance accounts for the arcuate nature of the chains and for the bunching together of the folds near the obstacle, a structure to which the term *virgation* is applied. In the case of the Jura and the Swiss Alps the obstacles appear to have been the Central Plateau of France and the Vosges-Schwarzwald massif; while the whole arc of the Alps, from Genoa to the Iron Gates, represents the free advance between the southward-projecting bastions of the European block, viz. the Spanish Meseta and the Rumanian spur or extension of the Russian platform (Fig. 28, R.S.).[1]

The Alps proper

To east and south of the Molasse-land stretch the Alps proper, which may be divided into *Western* and *Eastern Alps* at the north-south line (Rhine-Line) through Chur (Fig. 75). The Eastern Alps have been thrust over the Western, but have in general been eroded away to the west of the Rhine-Line. Both Western and Eastern Alps override the Molasse-land.

THE WESTERN ALPS

In the Western Alps five subparallel belts may be recognized (Fig. 75), each distinguished by its own peculiar structures and rock types: the first four are arcuate towards the west and north:[2]

1. **The outer belt** of ranges, composed for the most part of limestones of Mesozoic and Cainozoic age. It includes the Maritime and Basses-Alps and the Subalpine Chains in France; but in Switzerland it is best divided into:

[1] The edge of the foreland has been partly over-ridden by the folded ranges and partly incorporated in them. Thus the Hercynian Massifs of Belt 2 and their Mesozoic cover are held to belong to the over-ridden foreland.

[2] Kober has instituted a subdivision of the Eastern Alps, but this need not be discussed here. *Bau u. Enstehung der Alpen*, pp. 19, 20. See also p. 190.

1*a*. The *Pre-Alps* of Chablais and Fribourg.

1*b*. The *High Calcareous Alps* that elsewhere border the Molasse-land. Important mountains: Diablerets, Jungfrau, Wildhorn, Dent de Morcles.

2. A discontinuous belt of **Hercynian Massifs** composed of crystalline schists, gneisses and granites: Mercantour, Pelvoux (Fig. 75, I), Belle Donne (II), Aiguilles Rouges (III), Mont Blanc (IV), Aar (V), Gotthard (VI). These massifs are portions of the Hercynian substratum of the foreland brought to the surface in denuded anticlinal "culminations."

3. **An axial belt** of crystalline schists and gneisses, partly Mesozoic, but mostly of greater age: The Graian, Pennine and Lepontine Alps. Important mountain masses are the Simplon-Ticino, Great St. Bernard, Monte Rosa, Dent Blanche, and Matterhorn.

4. A **"Root-belt,"** mostly highly metamorphosed Palæozoic and older rocks, often very steeply inclined. Stretches from near Turin past the Italian Lakes, eastward to the Valtellina.

5. A southern limestone or **Dinaric Belt** can be recognized east of the neighbourhood of Lago Maggiore. This last belt becomes much wider when traced to the east, where it passes into the so-called Dinarides, which are ranges arcuate towards the south-west. It comprises chiefly Mesozoic, but also older rocks.

Looked at in detail, the Alps are seen to be built up of rocks that have been pushed towards the north in all the belts save the Dinaric, in which the direction is reversed. Different explanations have been offered for this structure.[1] Kober and others would see it as the result of the two continental blocks of Europe and Africa moving towards each other and nipping, as in the jaws of a vice, the crust that lay between them.[2] The movement gave deep-lying opposing underthrusts, which in the more superficial layers induced outward overthrusting towards each mass (Fig. 77). In the parts of the Alpides between the northward-moving and the southward-moving "border chains" (Rand-Ketten) there is in Kober's view a median belt of "Zwischengebirge" or "Betwixt-mountains." In the Swiss Alps these latter are absent, for the compression was so intense that the two border chains have come together, meeting at the line between belts 4 and 5.

[1] Such a statement might well apply to almost every phenomenon in the Alps, as may be seen by perusing Heritsch's works cited above. The account given here is largely based on Heim, Staub, Kober, and Collet, whose works are cited on p. 187.

[2] See also O. Ampferer's idea of a central engulfing or down-sucking. *Jahrb. Geol. Bundesanst. Vienna*, vol. lxxiv, 1925, pp. 35–75; Heritsch-Boswell, *op. cit.*, p. 168; A. J. Bull, *op. cit.*, p. 114.

On the other hand, Argand and Staub, adopting Wegener's theory of continental drift (p. 9), claim a northerly drift of the two continents, with, however, a more rapid drift of Africa which made it appear to move northwards through the region of Tethys towards Europe (Fig. 78). In their view all the primary movement was northwards. The north edge of Hercynian Africa overrode the southern edge of Europe, and in doing so, forced the floor of Tethys to buckle into mighty folds that were driven against Europe "like great stony waves rolling onto a shore."

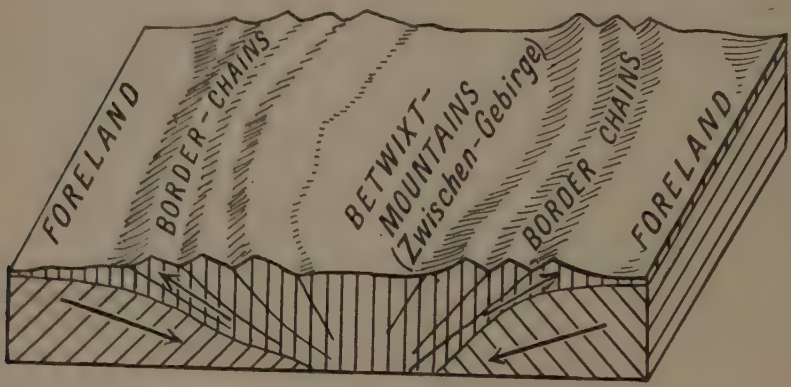


FIG. 77.—Diagram of a Typical Orogen, after Kober.

The Eastern Alps and the Dinarids they regard as part of Hercynian Africa, the Pennine and Lepontine Alps as the rucked-up geosyncline, and the High Calcareous Alps and Hercynian Massifs as parts of Europe. As Termier has put it, the Eastern Alps acted as a great crushing-sledge ("traineau écraseur") that by its passage produced all the deformation in the other tectonic elements. Everything was driven northwards, and the result was overturning in that direction in all the belts except in the Dinaric, where alone it is towards the south. The Dinarides are on this view a grand earth-backwash resulting from the resistance offered to the African drift by the packed rock-sheets of the Alps, a resistance which in effect produced a superficial counter-thrust from the north.

Mountain arcs in folded chains owe their elevation above their surroundings to tectonic causes, but it must not be imagined that the individual chains are necessarily upfolds. In very young and simple mountains, like the Jura, the anticlines often are ridges and the synclines are valleys (p. 177); but in the larger chains this is not so; for erosion proceeds concurrently while the mountains grow by the

piling up and packing together of rock-sheet after rock-sheet.[1] Valleys and peaks are soon carved from the elevated masses in a way that at first sight appears quite independent of the structure, though we may often see that it has been guided by the relative hardness of the rocks. Thus is laid bare for our inspection and study the internal arrangement of these, geologically speaking, recent chains.

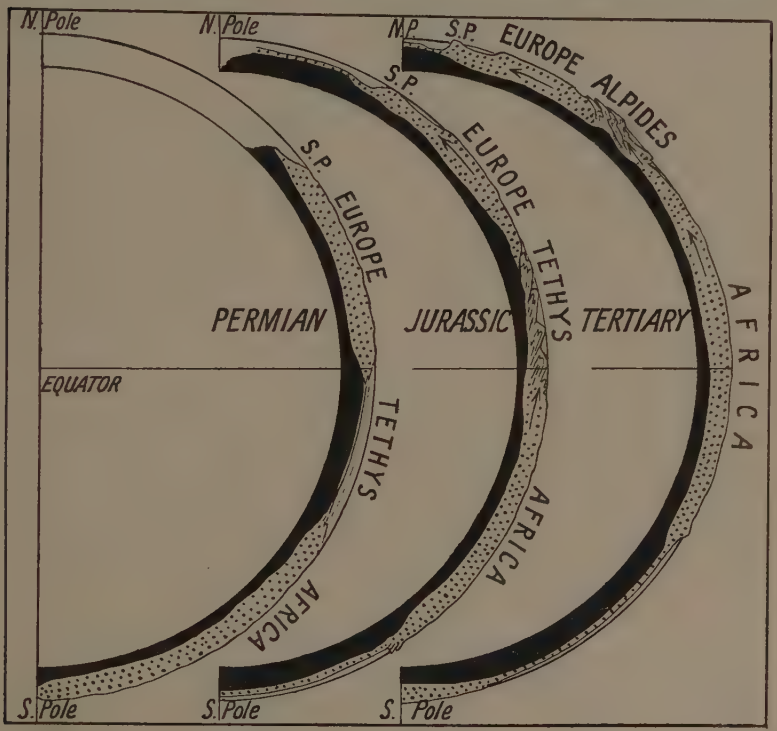


FIG. 78.—The Northward Drift of Europe and Africa; the buckling of Tethys to form the Alpides, by the overdrive of the hinterland (Africa) over the foreland (Europe).

S.P., Spitzbergen; full black, Sima; stippling, Sial. Not to vertical scale. Based on Staub.

THE INTIMATE STRUCTURE OF THE RANGE

The Nappe or Decken Theory.—This theory, which is now generally accepted,[2] claims that the Alpine chain owes its elevation

[1] Alb. Heim maintains that isostasy sets a limit to the height of mountains, and that the Alps were never much higher than they are now (A. Heim, translated by E. Montag, "The Summit-level of the Alps," *Proc. Liverpool Geol. Society*, vol. xv, 1928, pp. 90–109. See also Alb. Heim, *Geol. d. Schweiz*, Bd. II, p. 52, and "Weight of Mountains," *Proc. Liverpool Geol. Soc.*, vol. xiii, pp. 29–44.

[2] See, however, note 1 on p. 175.

to the piling up, one on another, of a series of translated rock-sheets, known as *nappes* or *decken*. These terms are synonymous, and are applied to translated rock-sheets of two types: (*a*) those that have been pushed into their present positions by lateral pressure as recumbent folds, i.e. anticlines that are so overfolded that their axial planes are nearly horizontal (Fig. 79); and (*b*) those that represent the crests

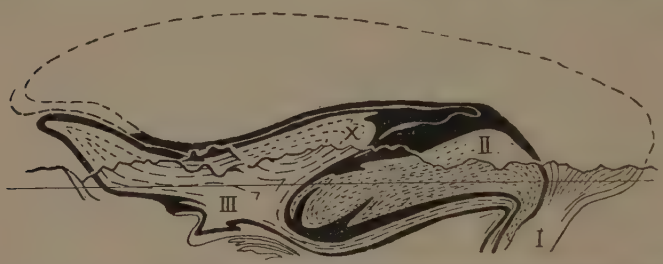


FIG. 79.—I, II, III, three Nappes of the recumbent-fold type; showing back-folding of III at X. Based on the structure of the Mischabel, after E. Argand.

White with lines, Crystalline cores; Full black, Mesozoics (schistes lustres).

and normal limbs of overfolded or recumbent anticlines that have been carried forward by thrust-faulting (Figs. 80 and 116). In the first type the reversed limb, though often rolled out, is, in theory, still recognizable; but in the second it is represented by a clean-cut thrust-fault. The frontal part of a nappe is frequently subdivided into a number of puckers or *digitations* by minor thrusts or overfolds.

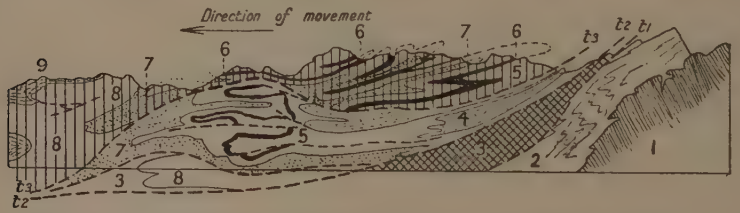


FIG. 80.—Section across the Mountains between Engelberg and Frutt.

1, Hercynian (Pre-Triassic); 2, Autochthonous Trias and Jura; 3, Tertiary; 4, Lias; 5, Dogger; 6, Oxfordian; 7, Valenginian (Base of Cretaceous); 8, Lower Cretaceous; 9, Upper Cretaceous; vertical shading, Säntis-Drusberg-Wildhorn Nappes; unshaded, Axen Nappe. Based on Heim.

Of the nappes dealt with in the sequel, those of the Pennine Alps belong to the first type (Fig. 79) and represent the squeezing together of the most plastic part of the geosyncline. The piling up and forward drive of these huge recumbent folds produced in the rocks over which they were forced, nappes of the second type (Fig. 80), especially in the High Calcareous Alps. In both types the growth of later

nappes is considered to have led to the folding and involution of pre-existing ones (Fig. 81), and continued pressure from behind may force the rear part of a nappe into and under its middle part, thus producing an appearance of overthrusting towards the rear; this is known as back-folding (Fig. 79, X).

Theoretically, nappes are entire or broken recumbent folds, and as such each is divisible into an anticlinal and a synclinal part. It is the anticlinal part that we see as thrust-sheets: the synclines between successive anticlines have been packed together to the rear and usually forced into a vertical posture in the so-called *root-zone* (Fig. 84). Occasionally we can see the recumbent anticline still connected to its roots, but where, as is usual, it has either been sheared off by earth-movement or isolated by erosion, the two parts can only be correlated by similarities of rock-facies.

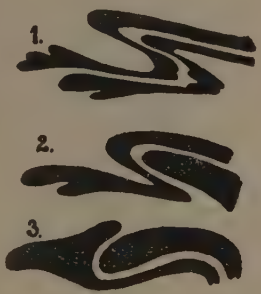


FIG. 81. — Involutions. After Albrecht Heim, from Collet.

The Importance of Facies.—In the area affected by the movements, Mesozoic and Early Cainozoic sediments originally lay as a thick cover over a platform consolidated and metamorphosed by the Altaid or Hercynian Orogeny. In the sequel, therefore, repeated reference will be made to the sedimentary cover as "*the Mesozoics*," though partly Cainozoic in age and partly now metamorphosed into schists, etc., and to the Pre-Permian and older rocks of the platform as "*crystallines*" or "*Hercynian massifs*." Depending on the depth at which the anticlinals that gave rise to the nappes originated, we find that certain of them are completely composed of the Mesozoic cover, while others are mainly made of crystalline rocks. Usually, however, each consists of a crystalline core together with part of the sedimentary cover (see p. 186).

In general, where nappes overlie one another, the lower have been transferred a shorter distance than the higher; usually also the higher and larger nappes came into being before those that underlie them (e.g. the Pennine on the Helvetian), though there are many exceptions to this rule. Sometimes subsequent erosion has produced a "window" (*Fenster*) in the higher sheets through which we may view the lower ones; sometimes it has proceeded so far that only outliers are now found. A nappe-outlier is known as a *Klippe*, e.g. the outliers of the Eastern Alpine Nappes found in Chablais and other parts of Belt 1 (Fig. 75 K and Plate I, A). Though each nappe may have originally travelled forward on a thrust-plane inclined at

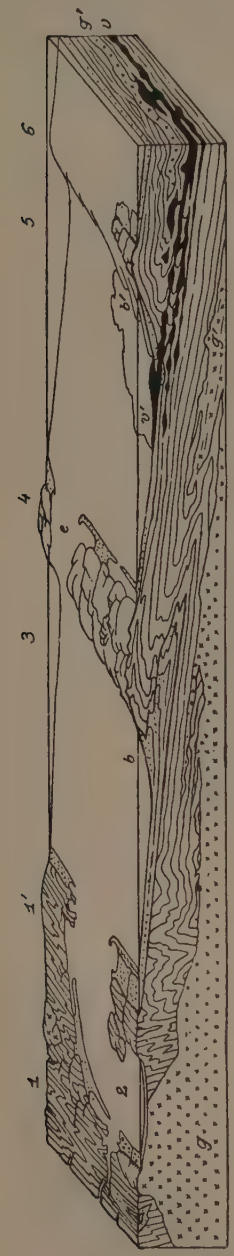


FIG. 82.—Embryonic State of a Chain of Alpine type. After Collet, *The Structure of the Alps*. Edward Arnold & Co. 1', Helvetian Geanticline on foreland (1); 2, Epicontinental Sea; 3, Foredeep or Geosyncline of Valais; 4, Frontal Cordillera or Geanticline of Briançon; 5, Geosyncline of Piedmont; 6, Second Cordillera or Geanticline of Dolin; *v* and *v'*, Basic intrusions; *b* and *b'*, positions of formation of breccias and conglomerates.

fairly uniform slope, like those first made known by Lapworth and others in the North-West Highlands of Scotland [1] (Fig. 116), prolonged and renewed pressure from behind has in the Alps crumpled and often overturned both nappe and thrust-plane, producing the most amazing contortion and involutions (Figs. 79, 80, 81).

It is thought by many that mountain-building on the scale of the Alps can only take place in geosynclinal regions,[2] in which a thick sedimentary cover has been accumulating, and in which the crust is carried by continued downsinking to levels where it becomes plastic enough to flow when subjected to lateral compression by the neighbouring continental masses. The movement of the latter towards one another may go on over protracted periods. In the case of Tethys the compression seems to have led to the buckling of the sea-floor into chains of islands and shoals as far back as Triassic times. We may therefore picture Tethys (Figs. 74, 78, 82) as covering the wide continental shelves of Europe and Africa between which it spread out as a geosynclinal sea with deep water in some places, but with shoals, reefs, and islands arranged as festoons running more or less parallel to the continental margins. The sea-floor was covered by sediments displaying a variety of facies corresponding to

[1] Geology of the North-west Highlands of Scotland," *Mem. Geol. Surv.*, 1907.

[2] For discussion of the geosynclinal concept, see Chapter XXI.

these belts and therefore themselves in belts subparallel to one another and to the margins of the continental blocks. As the movement went on, the original ups and downs of the sea-floor became accentuated, and finally in Tertiary times the whole was crushed together, the different facies-belts being piled one on another in such inextricable disorder that geologists have had to give the labour of a century to disentangle them. They have now, however, so far succeeded that they can use the facies displayed by the rocks to identify the position in the geosyncline from which they were derived, and thus refer them to one or other of the big groups of nappes, tabulated on p. 188.[1]

Fig. 83 shows diagrammatically the telescoping of the facies belts on to one another as a result of the earth-movements. With our

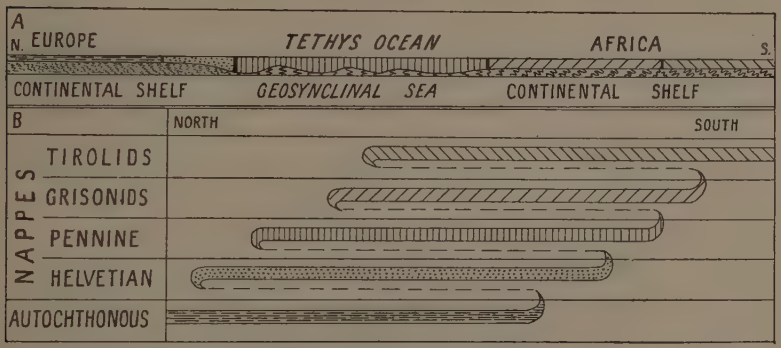


FIG. 83.—Diagrams to show (A), the different Facies of Mesozoic Deposits; (B), how they are superposed by the thrusting of the nappes. Adapted from Heim.

present knowledge it is possible to get some idea of the distance that the rocks have travelled. Heim has suggested that the nappes in the present 150 km.-wide belt of the Alps, if unfolded and laid out flat, would cover 600 or even 1,200 km.; and Staub considered the whole Alpine zone (in the extended sense of the term) to have a breadth of 1,800 km. now, but once to have extended over 3,000 or 3,500 km. This is a shortening equivalent of 15° of latitude (Fig. 78).

Sedimentary Nappes.—When viewed in greater detail the mountains are seen in some cases to be made of rocks, either as nappes or in their natural positions, that originally formed part of the belt of country in which they are now found. These are called *autochthonous*. Such are found in Belts 1, 2, and 5 (p. 188). In other cases a nappe no longer rests in its appropriate position, but has been carried forward to lie on rocks belonging to another part of the geosyncline

[1] von Bubnoff and Heritsch point out the reasoning in a circle implied in this argument. Heritsch-Boswell, *op. cit.*, p. 59.

and therefore characterized by a different facies. It is then termed *exotic*. The recognition of these two types by means of the facies is well exemplified in Belt 1 (the Pre-Alps and High Calcareous Alps of Chablais), which was definitely part of the continental shelf of Europe during Mesozoic times. Here in the lowest tectonic elements the Mesozoics are still in an autochthonous position overlying the Palæozoic floor (Plate I, A, autochthonous Mesozoics and Molasse). Parautochthonous nappes, i.e. nappes torn from a neighbouring part, may be thrust over them. These in turn may be covered by the exotic Helvetian nappes (stippled) consisting of Mesozoic rocks displaying distinctive facies indicative of their origin on the outermost edge of the continental shelf. The Helvetian nappes sometimes underlie others of Pennine facies (vertical ruling) that have travelled still farther, for they may consist of rocks deposited as bathyal strata in the main geosyncline or as neritic ones near the island festoons. Finally, as already stated (p. 183), there are found in the Pre-Alps klippe of East Alpine nappes composed of rocks with a Grisonid facies (diagonal ruling) which Argand refers to the continental shelf of Africa. In a single mountain-mass we may therefore see strata of similar age, but of four entirely different facies, brought into superposition by the earth-movements (see also Fig. 84).

Crystalline Nappes.—Apart from the Hercynian Massifs (p. 179), which are autochthonous and have only been broken by ordinary clean-cut thrusts (Fig. 84), the great crystalline masses of the Alps are now all regarded as the cores of gigantic recumbent folds. The Pennine nappes are the best-known examples (Figs. 79, 84), but the crystalline masses of the Eastern Alps are equally vast. The Hercynian substratum of the Pennine nappes in its descent below the geosyncline of Tethys underwent profound metamorphism; and it and the Mesozoic covering have also been greatly changed during the subsequent movements, and are now largely crystalline. The composition and degree of metamorphism of a crystalline core constitutes its facies, and its facies has served to help in the identification of the different groups of crystalline nappes now recognized.

The central belt of the geosyncline, owing to its thick mantle of sediments and to the plastic condition of its Hercynian substratum which had been depressed into the zone of flow, yielded early in the development of the Alps, and in it were born the crystalline nappes of the Pennine Alps in which can be recognized six main groups. The nappes, as has already been noted, are best regarded as of the recumbent fold type, because as a rule the Mesozoic cover is recognizable below as well as above the crystalline core of each, though it is frequently rolled out into a mere streak of lenticles. These nappes were piled on one another, but their forward advance was not neces-

sarily in the order of their superposition. Hence great complexity of interrelationship is noticeable, the nappes being intricately folded. Involution of one into, above, or below another is common. This feature is suggestive of up-thrusting and down-plunging of nappe into nappe. The instability of the pile of nappes seems to have been the cause of their lurching forward towards the foreland; and, as they moved, a lower nappe sometimes seems to have carried along on its back higher ones that had become inert, e.g. the Grisonid nappes of the Pre-Alps carried forward on the Pennine Nappes.

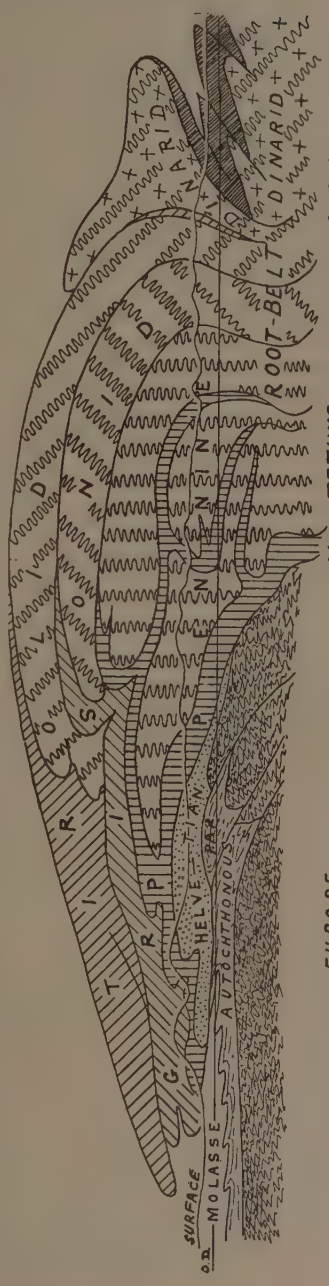


FIG. 84.—Diagram to show relation of the nappe-systems to the general structure of the Alps. The present profile is shown and indicates the vast amount of erosion.

PAR = parautochthonous nappe. Zigzag ruling indicates crystalline cores.

Tectonic Units of the Alps.

We may now consider the tectonic units of the Alps in the light of the modern conceptions of their formation that we have briefly sketched above.

The following classification and discussion should be read in conjunction with the sketch-map and generalized sections[1] (Figs. 75, 84, Plate I, A):

[1] They are based largely on A. Heim's *Geologie der Schweiz*, vol. ii, Pls. 26 and 27; R. Staub's *Bau der Alpen*, Tafeln I, II and III; L. Kober, *Bau u. Entstehung der Alpen*, 1923, Pl. VIII. See also L. W. Collet, *The Structure of the Alps*, 1927.

A. The Autochthon.—The Autochthon is essentially a part of the foreland: it embraces all those elements in the Alpine structure in which the Mesozoic and Cainozoic cover is still in place on the stumps of the old Hercynian mountains, both substratum and cover being approximately in their original position. Folding and thrusting is general; but the displacements are never large enough to carry strata far from their point of origin.

B. The Nappe Systems.—Each system comprises a set of nappes grouped together on account of their rock-facies, and each is regarded as derived from a different part of the geosyncline of Tethys. Table VII sets out the systems and the corresponding places of origin in the geosyncline and the present location of the roots of the nappes (following Argand and Staub).

TABLE VII

System.	Place of Origin in the Geosyncline.	Roots.
1. Helvetids or Helvetian nappes	Northern edge, on the continental shelf of Europe	In and south of the Hercynian massif
2. Penninids or Pennine nappes	The island-festoons and the central deeps	Northern part of the Root-Belt (Belt 4)
3. Austrids or East Alpine nappes	Continental shelf of Africa	Southern part of the Root-Belt (Belt 4)
(*a*) Grisonids or Lower and Middle East Alpine		
(*b*) Tirolids or Upper East Alpine		
4. Dinarids or Dinaric nappes	Continental shelf of Africa	More or less autochthonous.

We may now examine how these elements enter into the structure of the belts into which we divided the Western Alps (p. 178).

The Foreland

Jura and Molasse-land.—Entirely autochthonous.

The Alps Proper

Belt 1 (A). Pre-Alps.—This belt has an autochthonous substratum which is overridden by Helvetian, Pennine and Grisonid nappes. The Grisonid nappes occur in the Chablais as large Klippe, thought to have been carried here on the back of Pennine elements.

In France this belt widens out, and the Mesozoic autochthon forms a broad strip of mountain country in Provence.

Belt 1 (B). High Calcareous Alps.—This belt has also an autochthonous Mesozoic basis, though in places this has been torn away by the passage of overlying nappes. The latter are principally Helvetian Mesozoic nappes derived from south of the Hercynian Massifs, but the parautochthonous "Morcles" and similar nappes have been torn from the massifs, and appear as lower elements brought into being by the overriding of the higher nappes. Grisonid nappes are only represented by a few small Klippe, e.g. The Mythen near Schwyz.

The Helvetian nappes have their grandest developments in the depression between the anticlinal culminations marked by the Hercynian Massifs, from which latter they have disappeared by erosion.

The general structure of the whole of Belt 1 in Switzerland represents the over-thrusting of the relatively undisturbed Molasse-land by the Alps proper, these being here chiefly composed either of fairly local nappes (Helvetian) or of very far-travelled ones (Grisonid), both of which have plunged over the top of the Hercynian Massifs of Belt 2.

Belt 2. The Hercynian Massifs.—This is so called because the autochthonous Hercynian substratum here comes to the surface in anticlinal culminations as a series of crystalline massifs. These were the sea-wall of Europe against which the Pennine earth-wave broke. The massifs are subdivided into crystalline wedges by thrusts, and contain the roots of the parautochthonous nappes. Between the massifs are synclinal depressions in which the Hercynian substratum is hidden by the overriding Helvetian and Pennine nappes.

Belt 3. The Axial Belt.—This is mainly composed of the crystalline cores of the Pennine nappes and their enveloping sheaths of *schistes lustrés* (metamorphosed sedimentary). These nappes also surge into the gaps between the Hercynian Massifs, and in the Pre-Alps reach and over-ride the Molasse-land.

The piling up and forward travel of the Pennine nappes is held to be the cause of the thrusting and nappe-structure of the lower tectonic units observed in Belts 1 and 2.

Belt 4. The Root-Belt.—In this narrow belt we find the packed roots of the Pennine and Austrid or East Alpine nappes. The belt disappears below the alluvium of the Po in the south-west.

Belt 5. The Dinaric Belt.—Commencing near Lake Maggiore this belt widens eastward and becomes the Dinarides. The nappes are here autochthonous, but belong according to Argand to Hercynian Africa. They are overfolded towards the south.

The Eastern Alps

As already pointed out, the Western Alps disappear along the *Rhine-Line* below the vast nappes of the Eastern Alps, the Mesozoics of which are held to belong to the African side of the geosyncline. "Africa overrides Europe." [1]

The East Alpine nappes may have formerly spread more or less completely across the Western Alps, but have for the most part been destroyed by erosion. Their former presence is proved by the Klippen or outliers in Belt 1, to which reference has already been made (p. 183). Conversely, in the Eastern Alps occasional "windows" (Lower Engadine and Hohe Tauern) allow us to recognize the Penninids below the general spread of Austrid nappes, which here attain their grandest development (Fig. 75, E and T).

If the nappe-theory just outlined be the true explanation, one cannot but be staggered by the stupendous scale of a movement that has translated whole mountain-groups, and has literally heaped Ossa on Pelion. And the adequacy of the theory to explain the data is so complete that its only important rival, the "*Fan-folding*" of Albrecht Heim has been abandoned even by its author, who with great magnanimity has conceded the superiority of the nappe-theory by jettisoning the whole of his *Mechanismus der Gebirgsbildung* that had already become a classic, and by adopting the new conception in his master-piece, *Die Geologie der Schweiz.*

[1] There is much less unanimity in the interpretation of the Eastern Alps than of the Western; and there are features about them that will probably upset that unanimity. See Heritsch-Boswell, *op. cit.*

CHAPTER XVII

THE CAINOZOIC SYSTEM (*cont.*): THE ANGLO-PARISIAN CUVETTE AND THE BRITO-ICELANDIC IGNEOUS PROVINCE

A. The Anglo-Parisian Cuvette.

The Growth and Sculpturing of South-east England

The classification and general facies of the Cainozoic formations in the cuvette is:

Upper or Neogene	Pleistocene	Continental glacial deposits and river gravels (see Chapters XVIII and XIX).
	Pliocene	Shelly marine sands ("Crags"), estuarine clays, beach-gravels, etc., but deposits restricted, since much of the cuvette was land.
	Miocene	Great earth-movements. No marine deposits except in Belgium, owing to land conditions (Fig. 73).
Lower or Palæogene	Oligocene	Neritic, marine, estuarine and lacustrine deposits. Mainly estuarine.
	Eocene	Neritic marine clays (London and Barton Clays); estuarine and marine sands; estuarine clays. Mainly marine.

Present Distribution.

Palæogene deposits form the surface in South-East England in two synclinal areas, namely the Thames Valley (London Basin) and Dorset, Hampshire, Sussex, and the Isle of Wight (Hampshire Basin) (see p. 158, Figs. 66, 67). They also occur in the Paris and Belgian areas.

Neogene strata are limited to a few small patches of sands high up on the North Downs of Kent, and to a more extended outcrop nearly at sea-level along the eastern coast of Norfolk and Suffolk (Fig. 66). They also occur in Belgium, Holland, and North-West France.

Geography of the Palæogene.—During the interval between the "Danian" Chalk (p. 160) and the earliest Eocene deposits of

the Anglo-Parisian area, profound epeirogenic movements uplifted Western and Central Europe [1] into a great continent.

The uplifted Cretaceous strata were subjected to denudation that removed from the region the highest beds of the Chalk, and produced a very even plain (a peneplain). Epeirogenic movement had not, however, been absolutely uniform; and when examined in detail, the plain is found to cut across gentle undulations in the Chalk, so that the Eocene that covers it lies here on one zone and there on another, though at any one spot there is often no visible discordance of dip.

In the Eocene, the sea gained access to the Anglo-Parisian Cuvette or basin of sedimentation that had been brought into being by a subsidence cutting across the Armoricanoid trend in the older rocks that underlie it. The cuvette was bounded on the north-west by a coast-line probably stretching in a north-easterly direction across the English Midlands. Its general shape is shown in Fig. 72. Possibly it had one or more connections with the southern ocean (Tethys), and possibly at times with a northern one also. Two large rivers appear to have emptied themselves into the cuvette: one from the west in Devon or Dorset; the other from the south, not far from Paris. The area formed, therefore, a more or less enclosed basin, with large estuaries or deltas to the west and south, and a deeper marine portion to the north-east. Consequently we find in that direction an almost unbroken marine series which interdigitates westwards and southwards with estuarine and even lacustrine sands and clays, and more or less terrestrial deposits like lignites. Occasionally lakes were formed that had no outlet, and whose desiccation gave rise to gypsum deposits. Stamp has shown that in the English part of the cuvette, and probably in the Paris Basin also, the Palæogene deposits belong to six or seven minor cycles of sedimentation each "commencing with the deposits of a marine invasion followed by shallow, then deep-water marine beds. These in turn became gradually of shallower-water type as estuarine conditions spread seawards, and so pass into continental deposits." [2] At the maxima of marine submergence the cuvette appears to have been in communication with Tethys and on each occasion acquired characteristic Nummulites from those flourishing there. Though a continuous evolutionary series of these pelagic foraminifera appears to be present in the Alpine deposits, in the Anglo-Parisian Cuvette only isolated rungs on the evolutionary ladder are found. At the minima of marine submergence, estuaries and deltas

[1] Exceptions are Denmark, the Pyrenees, part of Provence, and the site of Tethys.

[2] L. D. Stamp, *Introduction to Stratigraphy*, 1923, p. 271.

built out the coast-line at the expense of the sea, and thus allowed the formation of lagoons, swamps, and freshwater lakes where formerly the sea had stood.

The wedge-shaped interdigitations of the continental and marine types in the west part of the Hampshire Basin into which the western river discharged, are shown in the diagram (Fig. 85) based on Stamp's work. The general permanence of the basin and the oscillation of the level of the sea relative to the coast-line

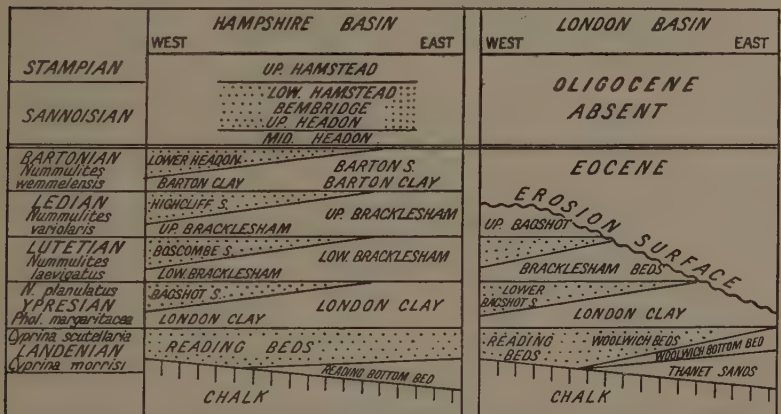


FIG. 85.—Diagram to illustrate the recurrence of Sedimentary Cycles in the Lower Tertiary of S. England.

Continental deposits, stippled (no indication of lithology implied); marine deposits, plain. Based on Stamp.

suggested to Stamp [1] that advances of the sea on to the land were determined by the intermittent uplift of the Wealden dome (p. 158). That this upfold was in existence as an island in Eocene times is proved by the presence in the Eocene beds of pebbles derived from the Cretaceous rocks of the dome.[2] Wooldridge, however, has brought forward strong evidence that the advances of the sea were really due to the epeirogenic deepening of the basin, rather than to the uplift of the Weald, though he concedes that the two movements may have gone on side by side.[3]

This general outline of Palæogene geography in the Anglo-Parisian region may enable the student to understand some of the difficulties presented by the various facies that characterize the

[1] L. D. Stamp, *Geol. Mag.*, lviii, 1921, pp. 108–14.

[2] e.g. Pebbles of Chert from the Hythe Beds (Lower Greensand) occur in the basal part of the Barton Series in West Surrey.

[3] S. W. Wooldridge, *P.G.A.*, vol. xxxvii, 1926, p. 180.

Eocene and Oligocene of South-East England. The fossils are the main guide as to correlation and in distinguishing marine from estuarine and freshwater deposits. They also permit us to realize that the climate of the cuvette must have been subtropical, the coasts being clothed with palms, figs, magnolias, as well as oaks and maple, and the seas swarming with southern types of shells. It is noteworthy that the plant-assemblage resembles that of to-day rather than that of the Mesozoic, and this is true of the animals also.

Geography of the Neogene.—By the end of Lower Oligocene times the Anglo-Parisian Cuvette was converted to a lake-covered plain, probably draining eastwards into a large sea stretching across Europe into Russia. The Alpine chain had begun to rise in the Oligocene, and the early Miocene saw the culmination of the first phase in its elevation which was not completed till much later. The uprise and building of the Alps finally eliminated Tethys, but it must be recalled that these geographical changes went on concurrently with others, amongst which two in particular affected Western Europe (Chapter XV).

(i) It was approximately in the Miocene that the westward connection with North America was finally severed. The edge of the present continental shelf of Europe appears to mark the westerly limit of the new Europe, parts of which were then, as now, under epeiric seas (p. 47).

(ii) Speaking generally, Central and Western Europe was uplifted by isostatic epeirogenic movements that produced in most places mere gentle undulations of the crust, but occasionally expressed themselves as sharp folding. There was also a good deal of dislocation by faulting. This vast region, the foreland of the Alpides, was in fact rocked by the "ground swell of the Alpine earth-storm" (Grenville Cole). The drainage of the new continent was blocked out in this eventful Miocene epoch, to which we must look in order to understand the present geography.

In Britain, with the exception of the deposits of a small lake [1] at Bovey Tracy in Devon, there is no sedimentary record of the late Oligocene and Miocene periods, and our knowledge of them is derived from a study of the earth-movements recorded in older formations. There seems to have been a general uprise in the north-west, that imparted a south-east tilt to the Mesozoic and Palæogene strata. At the same time in the south of England this general tilt was modified by folding oblique to it, and along roughly east-west lines. The large down-fold of the London basin is succeeded southwards by the Wealden up-fold, both major folds being

[1] Late Oligocene-Miocene in age, C. Reid and E. M. Reid, *Phil. Trans. Roy. Soc.*, ser. B, vol. cci, pp. 161–78.

in reality composites. In the Hampshire Basin we see the next major down-fold, which itself is terminated southwards in the Isle of Wight and in Dorset by a line of sharp monoclinal up-folds passing in places into over-folds and thrust-faults (Figs. 66, 67). During the Miocene the uplifted areas were gradually worn down to a peneplain, portions of which may be seen at high levels at many places in the south of England. The Wealden dome and the Chilterns were bevelled off into this peneplain (p. 36), which appears to have sloped towards the London Basin [1] and the region of the present North Sea, the latter constituting in Miocene times a major depression; for it was here that the sea reappeared in the succeeding Pliocene period. The earliest Pliocene deposits (the so-called Lenham Beds) occur, however, in irregular solution-hollows in the Chalk of the North Downs at about 600 feet; but the majority of the Pliocene rocks are found at low levels on the coastal plain of East Anglia. The sea in which they were formed, cannot have been deep, and consequently the distribution of land and water must have been more or less as now.[2] The East Anglian rocks are known as "Crags"; and are shelly sands, abounding in remains of lamellibranchs and gastropods, most of the species still existing, though some are no longer found in the North Sea to-day. Shelly neritic deposits of this type are not being laid down now off East Anglia, but are known to be accumulating on the Dutch coast. It has been deduced from this and other data that the currents of the Pliocene North Sea followed directions differing from those now prevailing.[3]

[1] S. W. Wooldridge, *P.G.A.*, vol. xxxviii, 1927, pp. 49–95.

[2] The difference in level between the Lenham deposits and the East Anglian Crags may indicate that the Lenham Beds have in the region of the Wealden anticline been elevated relatively to the Crags; in which case no great original difference in sea-level is implied. This explanation by isostatic tilting (p. 8) is supported by the apparent elevation of the above-mentioned peneplain in the North Downs, as maintained by Jukes-Browne (*Building of British Isles*, p. 406) and by Briquet, who has attempted to delineate the flexuring of the peneplain in Northern France and South England (A. Briquet, "La Peneplain du Nord de la France," *Ann. Geog.*, vol. xvii, 1908, pp. 205, 223).

Eustatic alterations of the level of the sea (p. 8) have also been claimed by Depéret, Lamothe, and others to account for the difference in level of the Lenham Beds and the East Anglian Crags (Ch. Depéret, "Essai de coordination chronologique general des temps quarternaires," *Comptes rendus Acad. Sci.*, vols. 166, 167, 168, 170, 171, 174, 1918–1920). This conception of universal alterations of sea-level is based on the discovery of old shore-lines of Pliocene and later ages at approximately constant levels in various parts of the Mediterranean. They have extended the application of the theory with less success, to regions where the data are more conflicting than in the Mediterranean, as for instance in the present case. The correctness of their general theory has still to be proved or disproved by more detailed investigation all round the shores of Europe (see p. 243). Some support in the present case has been given by E. W. Wooldridge, *Proc. Geol. Assoc.*, vol. xxxviii, 1927, p. 71.

[3] F. W. Harmer, *Q.J.G.S.*, vol. lvi, 1900, p. 732.

Towards the close of the period this sea had become virtually silted up by the deltas of the great European rivers; and possibly one of the distributaries of the ancient Thames or of the Rhine passed through East Anglia, leaving the estuarine deposits of the Chillesford Beds as its record. Their occurrences when plotted on a map have a sinuous course resembling the meanders of a great river.

The Cromer Forest Bed is the latest Pliocene formation. The so-called "Forest" consists of the stools of trees that had drifted down a river. It is associated with estuarine and freshwater deposits, the whole suggesting a marshy forest-clad plain traversed by a tidal estuary.

The geographical changes between the Palæogene and Neogene periods coincided with a lowering of the temperature in England. Unlike the subtropical fauna of the Eocene, the fossils of the Pliocene are temperate types, many of the shells still abounding along our shores. But even within the Pliocene it is possible to deduce variations in climate. The oldest or Coralline Crag contains southern forms that are absent from the succeeding Red Crag. This change may have been due to the severing of a connection with the southern ocean, but even so the temperate conditions of Red Crag times were modified later into a more Arctic climate as is recorded by the fossils of the Weybourne Crag. This was followed by a short warm period (Cromer Forest Bed). The advent of the Glacial conditions of the succeeding Pleistocene is evidenced by the appearance of many Arctic elements in both fauna and flora in the rocks that overlie the Forest Beds.

Earth-movements.—The English Miocene folds, which are often termed *Alpine* on account of their connection with the growth of the chain of the "Alpides," illustrate some general principles.

1. Relation of the thickness of deposits to folding.[1]

It will be recalled that throughout Mesozoic times the Midlands and the south of England were areas of great sedimentation. By the end of Palæogene times there had accumulated in them two thick lenses of slightly compacted sediment, each lens thinning towards the ancient massifs, and therefore lying in down-sinkings of the platform of consolidated Palæozoic rocks (Fig. 52). When the Alpine earth-movements exerted a lateral pressure on the crust, the lenses of new sediment were nipped between the rigid massifs and buckled upwards. Hence we find an anticlinal structure at the surface in those areas where the Mesozoic is thickest, and where during their formation there had been steady down-sagging. This principle [2] is best displayed in

[1] See especially G. W. Lamplugh, Presidential Address, Geol. Soc., *Q.J.G.S.*, vol. lxxv, 1920, pp. lxxiii–xcv.

[2] The same principle holds in geosynclines (see p. 261).

the Wealden area, where we see that a surface upward-movement amounting on the axis to some thousands of feet has not, on account of the great thickening towards the fold-axis, been sufficient to obliterate the synclinal arrangement in the depths. A surface anticline overlies a subterranean syncline (Fig. 86). On the other hand, the newer rocks overlying the Anglo-Belgian massif near London, on account of their relative thinness and by reason of the great height of the adjoining up-folds, came to form the London Basin. A surface syncline here overlies a buried anticline. The economic importance of the recognition of such a state of things

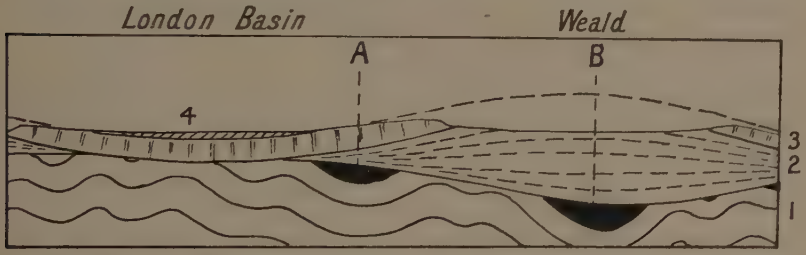


FIG. 86.—Diagram to illustrate the presence of an underground syncline below a surface anticline, and vice versa, dependent on original variations in thickness and subsequent folding.

A and B, hypothetical buried coalfields in the Palæozoic substratum. 1, Palæozoic; 2, Trias, Jurassic and Lower Cretaceous; 3, Upper Cretaceous; 4, Cainozoic.

is apparent from the diagram which shows folded coal-bearing rocks in a consolidated Palæozoic substratum, which at A are within reach though underlying a surface-syncline where at first sight they should be deepest; but unattainable at B, owing to the thickening of the newer strata and despite the surface anticlinal structure. The Kent coal-field is situated under conditions analogous to those indicated at A. No explorations have gone deep enough to prove the composition of the Palæozoic floor under the centre of the Weald, which is comparable to B.

2. Relation of newer and older fold-trends.

It has been pointed out that the arching of the Wealden Dome has the west to-east trend of the Armorican mountain-folding as developed in the rocks of the underlying Palæozoic platform. It is, however, probable that the adoption of this axial direction is due not so much to the renewing of those folds as to the fact that the southern side of the Anglo-Belgian massif was also parallel to, and determined originally by, that system of folding. Under lateral stresses the newer rocks would tend to crumple along lines subparallel to the edges of the rigid massifs, which in this case appears to have

coincided in direction with the Armorican fold-trend. We do not know how far this is a principle capable of general application; but it is perhaps significant that three dominant trends can be recognized in folds of this age (Fig. 66) and that these trends are parallel to three well-known directions of earlier folding. Thus the strike of the folding and tilting follows the west-east Armoricanoid direction in the south; the south-west to north-east Caledonoid direction in the South-East Midlands; and the north south Malvernoid or Pennine direction in Lincolnshire and South Yorkshire.[1]

Development of Drainage Systems.—To students of the physical geography of England the "Alpine" movements are of prime importance, for it was they that, as it were, rough-hewed the block from which by slow degrees denudation has since carved our present topography. The primary directions of the drainage-lines were determined by the up-folds and down-folds, and by the tilting. We see, for instance, the Lower Thames and the Kennet following the down-fold of the London Basin, and the rivers of the Weald flowing north and south from the axis of the Wealden Dome (p. 20). W. M. Davis suggested that the Thames Basin and that of the Ouse are profoundly modified remnants of systems that, originating on the tilted Mesozoic rocks, once stretched back into Wales. A consideration of this problem would involve too great a digression for a volume of this size, but readers should consult the works referred to.[2]

So great have been the changes and so enormous the volume of rock destroyed since the initiation of land conditions in England in Oligocene and Miocene times that it is difficult to picture the country as it was then; nor can we yet trace out the stages by which the present topography has been evolved; for we know very little about the changes in the level of the land relative to the sea, and we have only the most meagre remains of littoral and continental deposits and scattered relics of bygone topographies from which to deduce the history. Amongst the latter we must reckon the fragments of elevated peneplains (p. 195) that have escaped subsequent denudation. Each implies a prolonged period of erosion during which a plain was carved out by the rivers and sea, and graded with reference to a particular sea-level (p. 38). We have already referred to the well-marked example, formed during the late Miocene and early Pliocene periods, which is generally recognizable at high

[1] Much of the post-Triassic folding and faulting in the Midlands is also probably of Cainozoic age.

[2] W. M. Davis, "On the Development of certain English Rivers," *Geogr. Journ.*, vol. v, 1895. S. S. Buckman, "On the Development of Rivers," *Nat. Sci.*, vol. xiv, 1899. Lord Avebury, *Scenery of England*, 1904, chap. xi.

levels in inter-stream areas and on summits as stretches of almost level ground, in Cornwall at about 400 feet, on the Chilterns and North Downs at 400–600 feet, and in the Boulonnais (Northern France) at 500–600 feet.[1]

Although we cannot trace out the identical stages by which the present topography has been developed, we may learn a good deal about the methods by which it has been produced. For this reason the following account of the scenery and drainage of the Wealden area is introduced here, the region being chosen because of its simple geological structure, and the fairly clear relationship existing between that structure and the main physical features. The development of the topography in this case seems to be spread over almost the whole of Cainozoic and Quaternary time,[2] and is still proceeding.

Let us recapitulate what has been said of the structure, and give a brief description of the present topography and drainage as a preliminary to an attempt to outline the development of the latter. In the first place the term, the Wealden area, is here used to embrace not only the Weald proper, but the escarpments of the Greensand and Chalk that border it. The rocks of this area are the denuded relics of the elongated Wealden Dome, whose axis runs east and west midway between these escarpments. Its northern limb passes into the southern limb of the basin underlying the Thames Valley. The Lower Cainozoic rocks found in the latter may, in part, have once been continued over the crest of the Wealden Dome; but at present that area is floored by Cretaceous sediments, successively older and older strata being met with as the centre of the Weald is approached (see Figs. 66 and 87).

The Weald in the true or restricted sense of the word is the plain of Kent, Surrey, and Sussex, and is composed of the sands and clays of the Wealden Formation (p. 161). Ringing it round with varying continuity is the escarpment of the next younger subdivision, the Lower Greensand (p. 161) with its comparatively barren dry sandy soil, heaths and pinewoods. Separated from the Greensand ridge by a narrow strip of cultivated land, marking the outcrop of the Gault Clays, the Chalk Downs rise steeply as an outer encircling ring of dry grass-land. Here the absence of brooks and rivers, save in the deepest and biggest valleys, is the most conspicuous feature and one that supplies an explanation of the resistance that so soft a rock offers to mechanical erosion. The surface dryness is due to the extreme porosity of the limestone, which causes the

[1] See reference on p. 195.

[2] Some phases of the development more particularly connected with events of Quaternary time are dealt with in the next chapter.

rain to sink in rather than to run off as surface-streams. Hence its outcrop, unlike that of the adjoining strata, is in general not exposed to transportation and corrasion by surface-streams; and as a result tends to stand out as high ground. At the present-day denudation of the Chalk is largely effected by underground water; and it is thought that the numerous deep but dry valleys that seam its outcrop were excavated by stream erosion during the glacial period (p. 231).

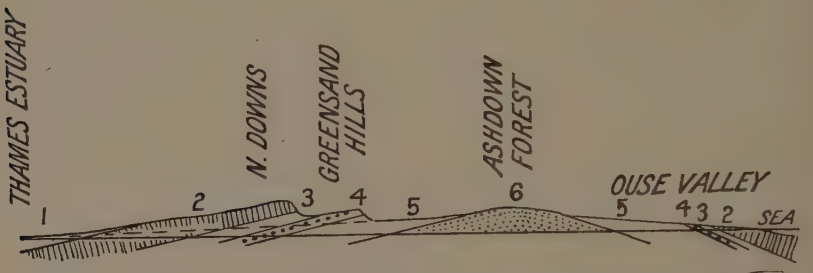


FIG. 87.—Generalized section across the Weald, crossing the escarpments in the north, but following the Ouse valley on the south of the Wealden Axis.

The thalweg of the Medway through the northern escarpments is indicated by the broken line. Non-resistant strata left plain. 1 Cainozoic, 2 Chalk, 3 Gault, 4 Lower Greensand, 5 Weald Clay, 6 Weald Sands.

It may be seen from the foregoing description of the Wealden area that it is characterized by roughly concentric outcrops of the different Cretaceous formations, the oldest in the centre and the newest towards the periphery, each constituting a belt of country marked out by its own physiographic peculiarities. The plain with its encircling escarpments, looked at broadly, may therefore be likened to an oval saucer [1] surrounded by a double rim which is now incomplete, for the Straits of Dover have cut through it in the east. The centre of the saucer is slightly elevated in the sandy hills of Ashdown Forest, around which the plain of the Weald Clay runs as a great depression. The double rim is formed by the parallel escarpments of the Lower Greensand and Chalk Hills, the former being locally discontinuous. Each escarpment is an elongated ridge, from the crest of which the ground falls steeply on the side facing the Weald proper and gently in the opposite direction. The gentle slope is known as the "dip slope," because it is more or less parallel to the dip of the strata, which, it will be recollected, is out-

[1] It must not be forgotten, however, that the central part of the saucer is and always has been drained by rivers that breach the rims, and is therefore higher above sea-level than the river channels at the breaches.

wards from the Wealden axis (Fig. 66). The steep slope is called the "*scarp*" or "*scarp-face*," and represents the broken or basset-ends of the beds. Escarpments of this type are found where a resistant stratum lies more or less horizontally over softer rocks. The dip-slope is gentle because here the streams have to work on a resistant flat-lying formation, but the scarp-face is steep because there the underlying softer rocks are being removed more rapidly than the more competent cover (Figs. 87, 88).

The escarpment ridges of the Wealden area are broken at a number of places by fairly narrow transverse valleys, through which the drainage of the saucer escapes to the sea. The valleys that breach the northern escarpments are occupied by northward-flowing rivers (Wey, Mole, Medway, Stour),[1] while many smaller streams rise on the escarpment and flow northwards to the Thames. The South Downs are, on the other hand, breached by southward-flowing rivers (Arun, Adur, Ouse, and Cuckmere). The directions in which the streams flow in crossing the escarpments is therefore the same as that in which the rocks forming them are dipping (Fig. 87).

In trying to unravel the connection between the geological structure and the present topography we must imagine what would happen if a flat surface, such as existed on the floor of the Chalk Sea, were elevated into an elongated dome.[2] In the first place an island would arise, and this, it has already been pointed out (p. 193), actually did occur here in early Cainozoic times. Secondly, the rainfall on the island would run off by a large number of small streams, the directions of which would be radial, and the inevitable consequence of the slope of the sides of the dome. In other words their directions would be governed by the geological structure. Such streams are called *Consequents*.

If we look at the present-day complex drainage and the curious saucer-like topography it is at first hard to recognize in it any resemblance to a simple dome-shaped island drained by numerous radial streams. True, the main rivers of the Wealden area flow away from the axis of the up fold and thus far conform to what might be expected, and the numerous consequent valleys that seam the Chalk-outcrop may be regarded as relics of an original radial system of streams. Yet instead of a great number of more or less radial rivers, we have now only nine which drain the whole area by a plexus of tributaries.

[1] The Darent breaches the North Downs, but not the Greensand escarpment.

[2] It is not implied here that the denudation of the Wealden Dome was entirely, or even mainly, pre-Cainozoic. Three separate uplifts took place, as is made clear in the sequel.

The following paragraphs attempt to outline the process by which what we see to-day has been developed from what we reason to have been the primordial condition. Behind the whole development, two governing principles may be discerned: namely, the tendency for rocks to stand out as hills in proportion to their capacity to resist erosion (p. 38), and secondly the tendency for rivers to increase their catchment basins in proportion to their activity, and at the expense of their less powerful neighbours (p. 38).

In very early Cainozoic times, the Wealden island in the Cainozoic sea had its surface composed entirely of Chalk, which rose to a considerable height in the axial region. Of its numerous radial stream-courses, many may have been subterranean. In some respects the region may have resembled the Karst limestone district of Istria, near Trieste, with its rivers running in deep clefts and through underground channels far below the general surface of the country. In the course of time the island became profoundly denuded, the Chalk being completely eroded away in the centre. We know this because we find pebbles of Vectian chert in the Lower Eocene rocks.

The island, however, seems to have been submerged in Upper Eocene times and buried beneath a blanket of sediments. When the late Oligocene and Miocene earth-movements re-elevated the Wealden Dome, the drainage that originated on these sediments was again radial. The streams on the north flowed to the Thames, which it will be recalled still runs to the sea on Cainozoic strata in the synclinal London Basin. The Cainozoic deposits were soft, and in the anticlinal region of the Weald were quickly denuded, the rivers coming to flow once more on the Cretaceous. Erosion continued until in late Miocene times the anticlinal region had been bevelled off to form the peneplain that has already been referred to (p. 195). Part of the peneplain became submerged below the Pliocene sea, but when uplift was renewed, the rivers again acquired fresh cutting power, and the present topography began to be carved. It is obvious that it is almost impossible to distinguish the denudation phenomena of these three main Wealden uplifts, but the general trend of the land-sculpturing seems fairly clear.

Formation of Escarpments.—As long as the consequent streams were all on or in the Chalk, denudation was slow, but as soon as any one of them cut through to the underlying soft Gault Clay, and it would first do so in its upper reaches, it proceeded to work more rapidly; for the easy removal of the clay led to the steepening of the gradient and consequently to an increase in the velocity and erosive power (Fig. 88 and Chapter III, p. 26). Undercutting of the Chalk also occurred, and was followed by landslips and the

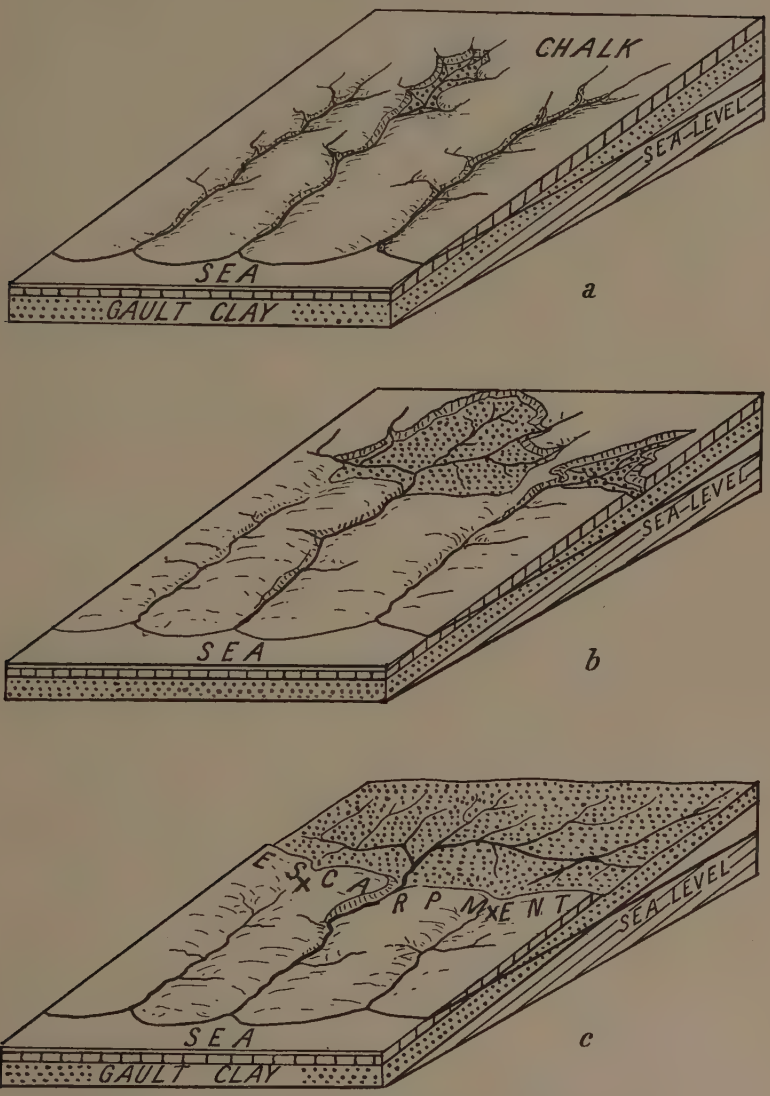


FIG. 88.—Diagrams of the gradual development of three consequent rivers, the middle one being more powerful than the others.

Stippling shows the outcrop of the Gault Clay laid bare by erosion. The beheading of the head-waters of the two weak streams gives rise to wind-gaps (X). The escarpment faces away from the observer, and is breached by the water-gap of the middle stream.

formation of springs at the junction of the Chalk and Gault. Both these factors would increase the rate of erosion enormously; for down the sides of the consequent valleys were now initiated *subsequent* tributaries,[1] of which those at work on the Chalk made but little progress compared with those on the Gault. By this process of differential erosion the Gault outcrop in each river-basin tended to be lowered rapidly and to grow until it became a plain surrounded by escarpments of Chalk. The destruction of the latter gradually extended both towards the axial regions and towards the sea, but at different rates (Fig. 88*c*). From the former, for the reasons given above, it was comparatively quickly stripped off; but down-stream the consequent rivers and their tributaries, as a result of the Chalk descending to below sea-level, have even to the present day to work on its resistant surface.[2] Thus early in the development of the Weald the Chalk stood up as an escarpment, because, as the river-system was gradually etched into the country, the Chalk could not be attacked so successfully as the neighbouring Gault. A second result of the denudation of the Chalk from the axial region would be the coalescence of the Gault outcrops of the different river-basins into a central plain, and the establishment of continuous escarpment of Chalk all round the axial region, save where, following their original directions, the *consequent* streams escaped through the girdle of hills. Here we see the beginning of the saucer-shape of the Weald. The escarpments of the Chalk have been, and are still being, sapped by the rapid removal of the soft Gault along the scarp-faces, a process that tends both to keep these slopes steep and to widen the plain at their feet. As long as the sea maintains the same level, the Chalk ridges must gradually shift their positions farther and farther out from the Weald,[3] and at the same time become lower and lower. But the level of the valley-floor where a consequent stream passes from the Gault on to the Chalk acts as a local base-level for the river-course across the Gault, and below this level there can be no downward corrasion (p. 27). Hence the centre of the saucer must ever be higher than

[1] Tributaries of "*consequent*" rivers are known as "subsequent" streams, being only formed *subsequently* to the "*consequents*." Since the consequent streams are usually parallel to the dip, they flow across the grain of the country, and are therefore sometimes termed *transverse*; whereas their tributaries (the subsequents) are as a rule parallel to the strike of the rocks, and are therefore called *longitudinal*. A river flowing down the axis of a pitching syncline may be longitudinal in the sense that it is parallel to the strike of the beds on either flank of the syncline. It is none the less a *consequent*, e.g. the Thames in the London Basin.

[2] And even on the overlying soft Tertiary beds, as the Thames Valley with its synclinal structure is approached.

[3] For rate of recession of the escarpments, see S. W. Wooldridge, *op. cit.*, 1927, pp. 77–80.

the level of the river-channels where they pass through the Chalk escarpments.

The second inner rim of the saucer, the Lower Greensand escarpment, originated in a similar way to that of the Chalk, but at a later stage. The scarp-forming tendency is here due to the difference in resistance between the porous and fairly compact sandstones of the Lower Greensand and the underlying soft and impervious Weald Clays.

While the escarpments and plains of the Wealden area were in process of making, similar denudation elsewhere was producing the escarpments of the Cotteswolds and Chilterns and the intervening plains.

River-growth.—It remains to say something of the complex river-drainage found at the present day in the Weald. So far we have treated the drainage as having consisted of a large number of radial consequent rivers each with its own tributaries. We have now to account for the disappearance of the majority of the radial rivers and for the development of the network of streams, the more important of which are frequently those running at right angles to the original radial directions, and therefore to be regarded as *subsequents*. Though difficult to prove in detail, it seems probable that this has been brought about by the unequal size and activity imparted to neighbouring streams in the "ideal" radial drainage-system by local accidents [1] and inequalities of the ground. Thus those *consequents* which for any reason were the first to cut through the Chalk and reach the more easily eroded Gault, speedily outpaced the others. As a result, tributaries of the successful *consequents* encroached on the catchment basins of their neighbours, and in this way abstracted the drainage from them; thus increasing their own, and diminishing their rival's power (Fig. 88). Ultimately, the head-waters of the less successful of the two rivers were "captured" by the stronger; and the "beheaded" remnant now appears to us as a stream having the direction of a "consequent," but rising far from the axis of the uplift that originated the consequent drainage (e.g. the numerous valleys on the north side of the North Downs). The Medway and Darent provide an excellent example of such rivalry, which sometimes goes by the name of "river-piracy" (Fig. 89).

Beheading as a rule occurs concurrently with the evolution of the escarpments, and is recorded by them in the notches or low gaps that exist to-day at various points along their crests, each marking

[1] e.g. transverse monoclinal folds; see S. W. Wooldridge, *P.G.A.*, vol. xxxvii, 1926, pp. 181–6.

the place where originally a consequent river passed through the ridge when the whole river-system lay at a higher level. Each notch lies at the head-waters of a small stream which is all that remains of the original consequent river. Such riverless passes across the escarpment are called *wind-gaps* (Fig. 88*c*, XX), in contradistinction to the *water-gaps* through which consequents still flow. From a wind-gap there usually run two streams. The one that goes down the dip-slope is the beheaded consequent; while

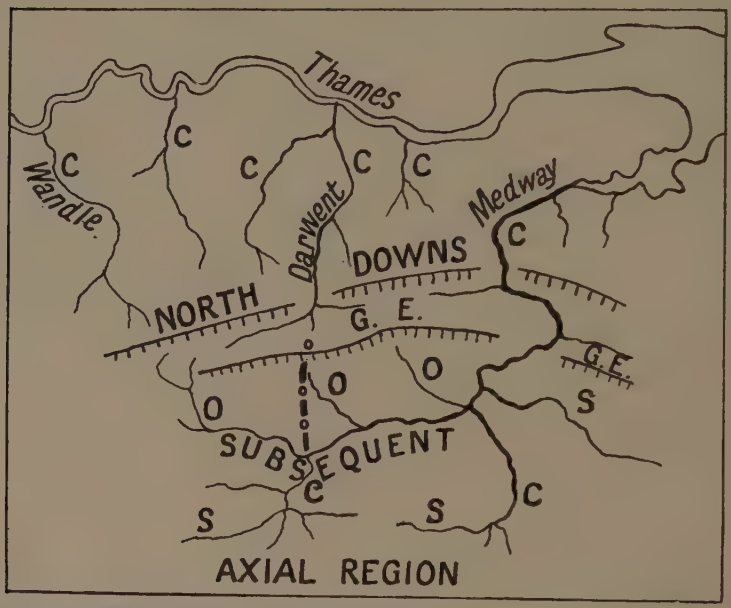


FIG. 89.—Outline Map of Medway-Darent river-capture. Heavy rings and dashes show the original direction of the consequent Darent before capture. Note the many beheaded consequent streams north of the N. Downs.

G.E., Greensand escarpment; C, Consequent; S, Subsequent; O, Obsequent streams.

the one that flows down the scarp, though it has the radial orientation of a consequent, pursues the opposite direction, and is known as an *obsequent* (Fig. 89, O).

The river-plexus of the Weald plain consists therefore of a medley of consequent, subsequent, and obsequent streams, united into nine river-systems, instead of the original large number of radial consequents with their diminutive subsequent tributaries.

Summary.—It remains to remind the reader that the sculpturing of the Wealden topography has not been a simple, continuous process, but one in which the rate of erosion has varied with the

growth of the Wealden Dome, with changing sea-levels, and with the youth or maturity of the river-systems. As already pointed out (p. 201) the process began in Eocene times; but the Eocene Wealden island was probably submerged and buried beneath sediments during the later part of that period. The mid-Oligocene movements uplifted these into a much larger land-area, on which a radial drainage was again established. Gradually during Miocene times a peneplain was produced that was related to a sea-level higher than the present one. This peneplain was somewhat modified by the marine erosion of the Pliocene transgression (Lenham Beds, p. 195) which had the effect of greatly diminishing the land-area. The lowering of the sea-level in later Pliocene times added part of the early Pliocene sea-floor to the land, and extended the river-system seawards across the emerging coastal plain, at the same time rejuvenating the rivers so that a new cycle of erosion was initiated. There has not yet been time for this cycle to be completed by the production of a new peneplain, though the height of the sea relative to the land has only varied within moderate limits (p. 243) during the Pleistocene, in which epoch the glacial conditions dealt with in the next chapters were not without influence on the development on the topography (p. 230).

B. The Brito-Icelandic Igneous Province

The similarity of the Lower Tertiary faunas of North America and Europe (both terrestrial and marine) indicates a much closer connection between the two continents than now exists. Their separation in Cainozoic times was formerly ascribed to the foundering of the intermediate parts of the ancient continent of Atlantis (p. 73); but Wegener has urged that it is due to the westward drift of America.[1]

The vast movements of the crust involved on either hypothesis could not have occurred without large-scale displacements of the sub-crustal magma;[2] and of this there is abundant evidence in the enormous igneous activity that showed itself over the region extending from Iceland to Northern England and Ireland (Fig. 72) in Eocene times. As far as Britain is concerned, the area affected was then land, and was in many parts covered by lava-fields and active volcanoes, early counter-parts of the Icelandic vents of to-day. Not only so, but from the multitude of dykes, sills, and larger intrusions which have been laid bare by erosion in places where there are now

[1] Both views have recently been discussed by J. W. Gregory, Pres. Address Geol. Soc., 1929, *Proc. Geol. Soc.*, vol. lxxxv, pp. cxiii–cxxii.

[2] A. Harker, *Q.J.G.S.*, vol. lxxiii, 1917, p. xci.

no signs of the surface lava-flows, it is clear that the whole of this vast region was underlain by potentially-liquid magma that was actively forcing itself through the crust towards the surface. The persistence with which the dykes in Northern Britain follow a north-west trend (Fig. 147) suggests that these intrusions were guided by lines of weakness related to uniform tensional stresses; and J. W. Evans has urged that those stresses were due to a tendency of the continent to stretch south-westwards towards the north-westwardly directed East Atlantic Deep. He adopts Wegener's hypothesis, and considers this Deep to be connected with the westward drift of the Americas and of the Mid-Atlantic Ridge.[1]

Not only do we see in the British portion of the Province the more superficial volcanic manifestations of igneous activity, but erosion has in places laid bare the magma-filled plutonic chambers, from a study of which we can learn much concerning the nature of deep-seated igneous phenomena. For these reasons a large part of Chapter XXV is devoted to a study of the Province.

Our knowledge of the climate of Antrim in Cainozoic times has been deduced in an interesting way. The weathering that some of the lavas underwent before being themselves buried by later flows, produced red clays (boles) and bauxites (more or less pure hydrated Aluminium Oxide, sometimes pure enough to be a source of Aluminium). Such weathering is held to show that the north of Ireland enjoyed a tropical and probably semi-arid climate; for a study of present-day bauxites and lateritic soils seems to have demonstrated that alternate wet and dry seasons, and fairly high temperatures are necessary for their formation. The nature of the plants occasionally preserved as fossils in sediments intercalated with the lavas confirms this deduction.

[1] J. W. Evans, *Proc. Geo. Soc.*, vol. lxxxi, 1925, pp. ci–ciii.

CHAPTER XVIII

QUATERNARY PERIOD: THE GLACIATED AREAS

Though in no way comparable as regards length of time with the Secondary or even the Tertiary period, the epoch from the close of the Pliocene to the present day has been elevated to the rank of a major division of geological time by egotistical man. It was originally regarded as embracing the period in which man, as a tool-using animal, first made his appearance, and during which he has evolved to his present state. In recent years evidence has been brought forward to show that man, as above defined, may have existed in Pliocene or even earlier times; but there is no unanimity in accepting this view. Hence it is convenient to retain the term Quaternary but to define it as post-Pliocene time. It may be subdivided into:

2. Holocene or Recent.
1. Pleistocene or Glacial.

In the sequel we shall not deal with the Holocene, for throughout its duration the shape and relief of our country, and its climate, fauna, and flora have all been much as at present; but in the Pleistocene this was not the case. The most remarkable difference was in respect to climate, which was at times more genial than now, but at other times became so Arctic that vast ice-sheets covered most of Britain and much of the Continent. Amazing oscillations in sea-level also took place, which profoundly affected the shape, size, and drainage of our country.

The history of the Quaternary period must appeal to any thinking man, for it is the record of the last stages in the growth and evolution of the present land-surface, its drainage, topography and coast-line; and of the fauna and flora it supports. Not only so, but in it we can follow—indistinctly perhaps at present—the changes of climate and environment under which the human race parted company with the brutes, and struggled through long ages of savagery and varying stages of civilization to the point at which history picks up the threads of the story.

The type of data from which the history of the Pleistocene has to be deduced differs considerably from that drawn upon in the other geological systems. Marine deposits of the period are generally inaccessible, and we have to rely upon scattered and local continental

deposits that are often glacial in origin. Many of these unconsolidated formations have been deeply ravaged by the enormous erosion that accompanied the glacial climate, which also militated against the existence of a large fauna and flora, so that the deposits are often unfossiliferous. Of the organisms preserved it may be said that in any one region they differ from epoch to epoch, more as a result of the varying climates under which they lived than as the outcome of evolutionary changes in themselves. Consequently the stratigrapher is to a large degree deprived of suitable fossils for correlation purposes, and has even been driven to use the varying fashions in man's tools for that purpose.

Considerable changes in sea-level, to which reference has been made, can be demonstrated; but they are not well understood. This greatly adds to the difficulty of interpreting the geography of the period.

We shall now attempt to trace out some of the factors that have influenced the evolution of the present topography of this country during Pleistocene times, and in so doing we shall gain an insight into the workings of glaciers and ice-sheets. Many of the results of former ice-action have been seen in process of formation in regions at present subjected to glaciation; but others have not, and no doubt were produced under conditions that preclude the possibility of observation until the ice has disappeared. In fact our knowledge of some glacial processes is almost entirely inferred from the records that Pleistocene glaciers have left behind.

It is from these two view-points—as a demonstration of glacial phenomena and as a record of the last stages in the evolution of the present topography—that it is proposed to examine the Pleistocene of Britain.

For the purpose of considering the evolution of the present topography, Britain can be divided into two regions:

(1) Glaciated—includes all Ireland, Scotland and Wales, and England as far south as a line joining the mouth of the Severn to the mouth of the Thames (Fig. 90).

(2) Unglaciated—Southern England.

Within the limits of the Pleistocene there were, as already mentioned, *interglacial* episodes with a genial climate, and *glacial* episodes, with an Arctic one. Though there is not much record of the effects of the interglacial genial climate in the glaciated area, there is on the other hand abundant proof in the unglaciated part that the country was subjected to abnormal conditions during the glacial episodes. It will, however, be convenient to consider the two areas separately.

The Glaciated Areas

The advent of a glacial episode would first be felt in the mountains. Ice-fields and valley-glaciers would spring into being, but as the glacial conditions became accentuated, the valley-glaciers would gradually amalgamate and form ice-caps and ice-sheets which, spreading far and wide, would bury hill and vale alike. With the oncoming of more genial conditions the reverse would take place. We would expect to find a record of the second set of valley-glaciers, but not of the first; and this in fact is the case.

Fig. 90.—Lines of ice-flow and limits of glaciation in the British Isles. Unglaciated areas stippled.

Valley-glaciers.—In the mountainous districts of our country, more especially the Highlands of Scotland, the Lake District, Snowdonia, and the Irish mountain-masses, the record of the valley-glaciers is conspicuous. The striations, roches moutonées, perched blocks, and moraines that constitute that record are so well known that it is unnecessary to describe them again, but we may comment on some less direct evidence. Many moraines hold up the drainage of the valleys across which they lie, to form lakes. This is especially

common in the cwms, corries or cirques at high levels. Characteristically these latter are steep-sided valley-heads in which nestle small lakes or tarns. It is now pretty certainly demonstrated that such peculiar valley-heads are being produced at the present day where a stationary ice-field gives birth to a moving glacier, the semicircular crack or bergschrund (rimage) which develops in the summer between the two, playing an important part in their origin. The crack admits thaw-water and rain, and allows changes of temperature in the rocks at the bottom of the crack. A more intense weathering takes place here than elsewhere under the ice, and provides material to be carried away by the glacier (see Fig. 18, p. 34). This differential erosion results in the production of steep crags below the head of the glacier. The precipices surrounding Llyn Idwal in Snowdonia are a good example of such crags laid bare by the disappearance of the ice. Some of the lakes in glaciated mountainous regions lie in hollows scooped out of the solid rock by the abrasion of the glacier; but many more, even if their outflow be over solid rock, occupy moraine-dammed valleys. Occasionally the damming has led to the diversion of the present river from the line of the pre-Glacial valley over the watershed into another drainage-basin. A conspicuous example of this is Windermere (Fig. 91).

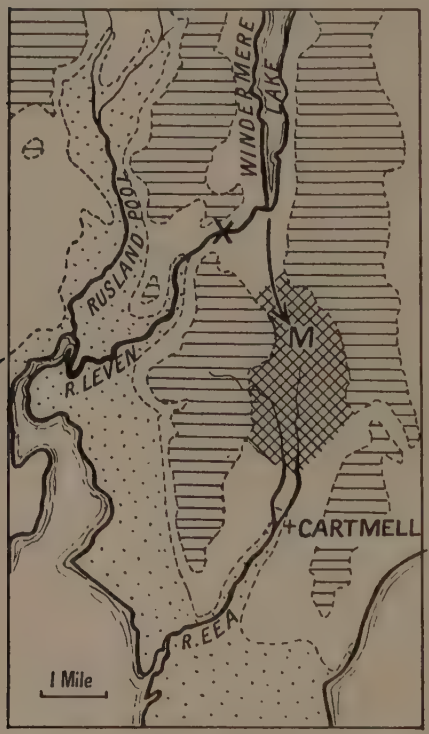


FIG. 91.—Sketch Map of the Windermere diversion.

Ground below 100 feet stippled, above 300 feet horizontally shaded. X, site of overflow; M, Moraine dam (cross-hatched); the arrow shows original direction of the Windermere river.

In some of the Highland valleys the moraines of valley-glaciers still present the tumultuous appearance due to irregular deposition which characterizes the terminal deposits of existing glaciers in the

Alps and elsewhere. Small lakelets occupy some of the hollows and the drainage is very irregular. The whole is in much the same state as when the ice left it, a feature that testifies to the lateness of its disappearance. Occasionally moraines are found that are roughly concentric and mark the retreat-stages of a valley-glacier that debouched from its mountain-course upon more open ground (Fig. 92). The expanded lowland part of such a glacier is termed a *pied-*

FIG. 92.—Crescentic Moraines round the mouth of the Caragh Valley, Co. Kerry. Lough Caragh covers the central basin from which the glacier deployed.

Based on W. B. Wright, *Quaternary Ice Age*. By permission of Messrs. Macmillan & Co., Ltd.

Moraine ridges black; arrows show glacial strial

mont-glacier. At the periods of maximum glaciation the great Alpine glaciers terminated in this way on the surrounding plains. Lakes Constance and Garda lie within the curved moraines of the former piedmont glaciers of the Rhine and Sarca valleys respectively.

In many valleys that have been occupied by glaciers, a characteristic feature is the step-like shape of the thalweg. This is said to be due to the differential erosion by the glacier, the corrasive power of which varies with the pressure it exerts, being great where the ice is thick and less where it is thin or broken by crevasses. Behind the narrow parts of the valley the ice piles up: thus thickened, it becomes better able to corrade than in the portions where its flow is unimpeded, and where it grows thinner as a result of deploying to occupy the

wider valley. A U-shaped cross-section, a general truncation of the lower parts of the spurs that project into the main valley, and the presence of "hanging" tributaries (i.e. side-valleys that are not graded evenly with the trunk-stream, but join it by rapids or waterfalls), all point to active erosion by thick and freely-moving ice in the main

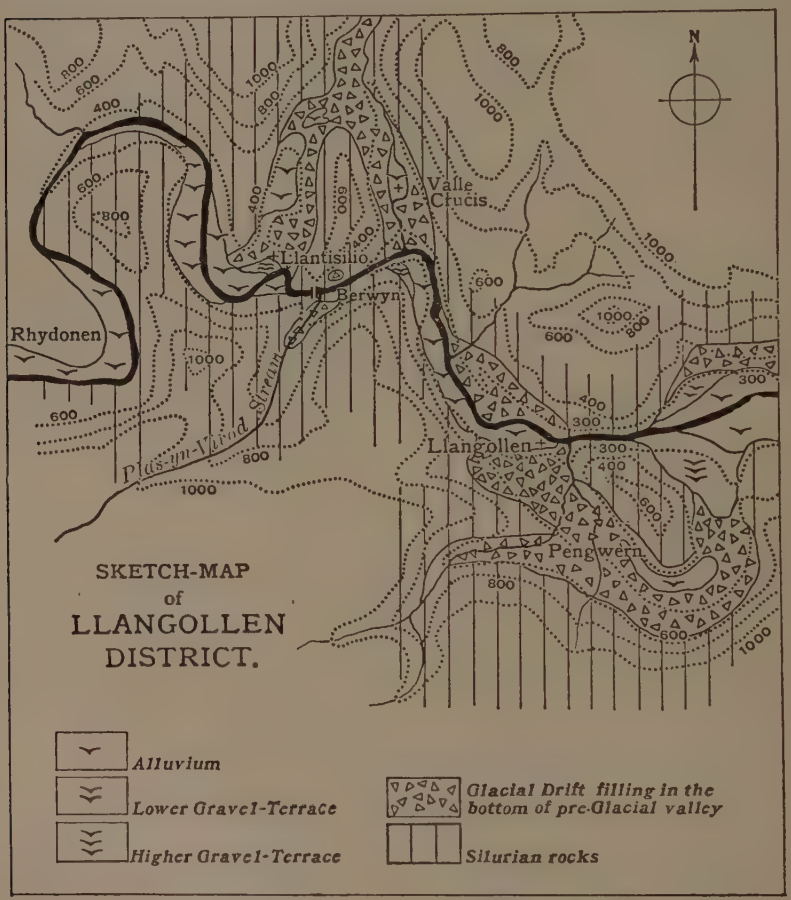


FIG. 93.—River Diversions in the Dee Valley near Llangollen. After Wills.

valley. Many of these features may be seen in the Welsh and Cumbrian hills, e.g. the hanging valley of Watendlath Beck at the Lodore Falls near Keswick, and the truncated spurs of the Pass of Llanberis, and of the Ceiriog and Dee Valleys near Llangollen.

In the Dee valley at Llangollen the influence of a valley-glacier

is recorded by two diversions of the river.[1] The valley here is very sinuous, and with an inner gorge that meanders round large spurs. During the melting of the ice, water appears to have flowed between the hill-sides and the glacier, and while the latter still buried the inner gorge, marginal streams began to cut across the necks of the spurs, and in two instances the channels then initiated have retained the post-Glacial river; and at Llangollen itself and at Berwyn the river flows in rocky gorges, while its abandoned sinuous course can be easily traced, though largely filled up with glacial deposits (Fig. 93).

Ice-sheets.—The features so far discussed are largely confined to mountainous tracts, and were produced by the latest valley-glaciers that lingered there after the bulk of the ice had disappeared. It is the mighty ice-sheets which preceded them that have so profoundly modified the drainage and shape of our land. For this reason the phenomena they produced deserve special attention. We have to look to Greenland or Antarctica for modern examples of glaciers on this scale, but there we can only observe the surface phenomena. In our country we can see things that were produced at the margin of the ice, in it and under it.

Fig. 94 shows the enormous area in Europe that was once covered by ice, though we do not know whether it was all buried simultaneously. The arrows show the general directions in which the ice travelled. It will be noted that the mountains of Scandinavia were the main centre of dispersal, but that Britain had several foci, some in the mountains and some on comparatively low ground in Ireland (Fig. 90).[2]

It is at first difficult to see how ice could travel such distances and in many places contrary to the slope of the land. Traverses across Greenland, however, have revealed the extremely low angle of slope that characterizes such ice-sheets, and it has become clear that, given enough snowfall, ice flows outwards from the centre of maximum accumulation like porridge piled up in the middle of a plate.[3] At the same time it is sufficiently rigid to transmit the pressure due to the difference in the height at the focus and at the margin, and thus force itself locally to move uphill.

The extent and direction of flow of the different Quaternary ice-sheets has been deduced from a study of their deposits which are commonly known as "*drifts*." These enormous glaciers corraded and striated their beds, and in some parts the local direction of ice-

[1] L. J. Wills, *Q.J.G.S.*, vol. lxviii, 1912, pp. 182–6.

[2] This has been questioned (see J. K. Charlesworth, "The Glacial Retreat from Central and Southern Ireland," *Q.J.G.S.*, vol. lxxxiv, 1928, pp. 293–344, and discussion).

[3] This simile is not meant to imply that ice moves exactly as a viscous fluid.

flow can be gathered from the striæ; but more frequently we rely on the presence of deposits demonstrably of glacial origin to tell us of the extent of the ice-sheets; and the direction of flow is determined by tracing the "erratics" or "travelled stones" in the drifts to the sources whence they were derived. Like the valley-glaciers, the ice-sheets carried a vast amount of debris, but unlike them, they derived the material more from below than from above. Soft rocks were ploughed up or torn up, so that masses a quarter of a mile or more

FIG. 94.—Sketch-map showing the maximum extension of the ice-sheets and valley glaciers in Europe.

I, Outer limit of "Old Drifts." II, End-moraine of "New Drifts." III, Baltic End-moraine. Arrows indicate directions of ice-flow; unglaciated areas stippled. Based on W. B. Wright and J. K. Charlesworth.

in diameter were sometimes incorporated and carried forward like boulders. In crossing the sea-floor, sand, mud and shells were picked up, transported and redeposited at great heights (e.g. 1,350 feet on Moel Tryfan near Carnarvon), so that marine shells in glacial deposits are no criterion of marine deposition or proof of submergence at the locality in question. The slow movements of the ice with its stone-shod base ground off a fine flour of fresh unaltered rock that, when redeposited, formed clays in which larger blocks were frequently embedded. The mingling of coarse and fine material is a feature

due to the absence of grading by water, and one that serves to differentiate these so-called boulder-clays from ordinary clays, from which they are also distinguished by the general absence of bedding. In summer, water played an important part around the edges of the ice-sheets. It flowed in channels on the ice or through tunnels in it and also issued from below it. Such running water ground up and rounded into small grains and pebbles the stones that reached it; and it transported and redeposited the material as sand and gravel.

Types of Glacial Drifts.

It is therefore clear that we may expect to find the presence of the Quaternary ice-sheets recorded in a very varied suite of deposits.

In Britain we can distinguish a region of "ancient drifts" that have lost their original surface-configuration as a result of prolonged erosion, from one of "newer drifts," in which the deposits frequently display characteristic topographical forms which help us in recognizing them and in making deductions as to the shape and position of the glacier or as to the direction in which it was moving. Since the "newer drifts" are generally preserved in much the same form in which they were originally laid down, it is to them that attention must first be directed.

Boulder-clay is found over large expanses and at very varying levels. Whilst usually giving rise to broad plains, it sometimes occurs in another characteristic topographical form, known as a *drumlin*. This is a low hogsback ridge, some hundreds of yards in length and perhaps a third as broad as long. Its longer axis is generally regarded as being roughly parallel to the direction of former ice-movement. If this is true, as drumlins frequently occur in groups, the general axial trend within the group should form a reliable indication of the direction in which the ice-sheet locally was travelling. Found pre-eminently in regions formerly covered by the great ice-sheets, drumlins have also been observed on the sites of the Quaternary piedmont glaciers of the Alps (p. 213). Fine examples of drumlins occur in Ireland, Southern Scotland, Cumberland, and North Wales.

Many spreads of glacial clay are comparatively stoneless, and it is probable that some of these occurrences mark the beds of ice-dammed lakes that have since disappeared. Much of the boulder-clay of the great drift plains round Chester and in the lower Dee valley probably falls into this category, as also does that of the Vale of Pickering (p. 226, Fig. 99). Such clays contain occasional stones dropped from melting icebergs.

In Sweden the glacial clays that were laid down along the retreating ice-front in the waters of the Baltic (sometimes a sea, sometimes a freshwater lake) are finely laminated, the layers being alternately

mud and silt. These so-called *varv-clays* owe their lamination to the difference in the rate of summer- and winter-melting of the ice, the silts representing the more rapid summer-rate. De Geer [1] has used this seasonal banding as the basis of an estimate of the actual length of time that has elapsed since the ice began to melt away in Southern Sweden (p. 239). Laminated glacial clays are found in Yorkshire and Cumberland, etc.

In Scotland fossiliferous marine clays have been proved to have originated under glacial conditions. They are characterized by Arctic types of molluscs, and by large boulders that evidently melted out of icebergs and fell on to the soft sea-floor.[2]

Gravels and *sands* are often associated with boulder-clays. In some parts of England there is very generally a series of these, forming a sheet between an upper and a lower clay; but the claim sometimes made that this arrangement indicates interglacial conditions between two glacial episodes cannot often be conclusively sustained. Apart from such cases, however, boulder-clay frequently passes laterally into, or is replaced by, sands or gravels. Yet the most conspicuous accumulations of the latter are often dissociated from the clays, and exhibit features which indicate that they were deposited along the edge of the ice; for in our own country coarse bouldery moraines that can be shown to have originated as terminal deposits of the ice-sheets, as distinct from valley-glaciers, are almost unknown; and their place appears to be taken by irregular mounds of gravel and sand (kettle-drift and kames) or by more evenly-sloping fan-shaped spreads (out-wash- or apron-fans). One of the most conspicuous moraines is that of the Vale of York, formed at the end of a lobe of the Teesdale Glacier (Fig. 99). Kettle-drift moraines are well seen in Ireland, and in Cheshire and Shropshire. They take their name from the term "kettle-hole" which is applied to depressions without outlets and often filled by lakelets, that characterize their surfaces. The mounds in the kettle-drift are often closely related to kames, which are more isolated irregular hills of sand and gravel that also originated along the ice-margin.

The Swedish term "*osar*" has commonly been regarded as synonymous with "*esker*." Both are applied to narrow elongated ridges of gravel and sand, but there is some controversy as to whether they are similar in origin. The Swedish "osar" are usually believed to have originated on a retreating ice-front that ended in the sea, and to represent a succession of small deltas thrown down by an en- or sub-glacial stream, whose mouth gradually receded as the ice melted. Long pauses in the retreat are represented by the widening of the

[1] See note on p. 239.

[2] J. Geikie, *The Great Ice Age*, 3rd edit., 1894, chap. xxi.

delta. On a map the long narrow ridge with its periodic widenings resembles a string of beads, and the structure is known as a beaded osar (Fig. 95). Osar are usually subparallel to the direction of retreat of the ice. The Irish eskers are ridges of sand and gravel which resemble osar in their general appearance and in the fact that they run indiscriminately across hills and valleys. They have been interpreted by Sollas as the filled-in channels of en-glacial streams, but recent work by Gregory and by Charlesworth seems to have proved that they are in reality terminal moraine-ridges.[1] The term eskers should therefore either be abandoned or else used in a purely descriptive sense.

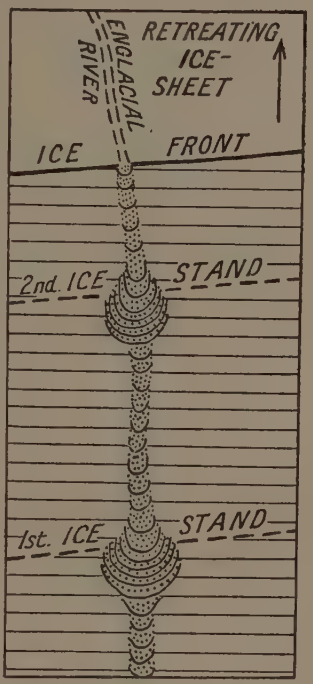


FIG. 95.—Diagram illustrating the formation of a *beaded osar* as the united deltas of an en-glacial stream in an ice-sheet whose front is melting in a lake or the sea. The thickenings or *beads* mark halts in the ice-retreat.

Stipple, sand and gravels of the osar (crescentic lines limit each year's deposit); horizontal ruling, the contemporaneous vary or laminated clay.

The topographical expression of the various types of glacial deposits just outlined is not found in the area of "older drifts" in the Midlands and East Anglia. In the latter region the deposits more usually occur in sheets having in general monotonously even contours; but owing to the great subsequent erosion at the higher levels prevalent in the Midlands the drift-sheet is there cut through by the rivers, and its relics come to occupy the inter-stream areas. Thus, much of Warwickshire is overspread by what appears to have been an outwash-fan of gravel and sand; but traced to the west and south-west into the drainage basin of the Warwickshire Avon, the sheet-appearance rapidly gives place to a series of small outliers capping the hills. The final stage of this process is represented by large isolated boulders, the sole survivors of former glacial drifts.

[1] W. J. Sollas, *Sci. Trans. Roy. Dublin Soc.*, ser. 2, vol. v, 1896, pp. 785–822. J. W. Gregory, *Phil. Trans. Roy. Soc., London*, ser. B, vol. ccx, 1920, pp. 115–51. J. K. Charlesworth, *Proc. Geol. Soc.*, 1928, p. 35; and *Q.J.G.S.*, vol. lxxxiv, 1928, pp. 293–344.

The Extent of the British Ice-sheets.—The deductions as to the shape, size, and direction of movement of the various British ice-sheets (not all necessarily contemporary) that have been made from a study of the drift deposits, is displayed in the map (Fig. 90).

It will be seen that the ice-sheets covered the whole of Scotland and Ireland, and passed out to sea. England, Wales, and the Irish Sea were also covered as far south [1] as the Bristol Channel, the Cotteswolds, and London.

The great centres of ice-radiation lay over:

The Highlands,
The Southern Uplands,
The Lake District,
Wales,
Donegal, Galway and Kerry in North and West Ireland,
Wicklow Hills in East Ireland.

Another ice-sheet, far vaster than the British, covered Scandinavia and the Baltic basin, spreading into Germany and across the North Sea until it came into contact with our British ice. This Scandinavian sheet appears throughout to have exerted a strong influence on the glaciation of Britain. There is evidence on the Durham coast that it was the earliest ice to exist there.[2] Numerous erratics also prove that it invaded Yorkshire and East Anglia. Its enduring domination is witnessed by the way the ice travelling eastwards from Scotland and Northern England was deflected, so that north of the Firth of Forth it was forced northwards, crossing Caithness, the Orkneys and Shetland Isles from the south or south-east; while south of the Forth it moved at first southwards parallel to the coast, and later invaded the Midlands and East Anglia from the north-east. Along the west coast of Scotland and the north and west coast of Ireland, the ice passed unhindered out towards the edge of the Continental Shelf which doubtless formed its westerly limit.

The third great line along which escape could be obtained was the Irish Sea. We find it occupied by one of the largest and most powerful glaciers fed from the Southern Uplands, the Lake District, and Northern Ireland. To a less extent it received ice from Eastern Ireland and Wales. This glacier was so powerful that it invaded the low-lying coastal regions of East Lancashire, North Wales and Ireland, overriding the Isle of Man, the Lleyn Peninsular and Pembrokeshire. It even thrust a lobe into the heart of the Midlands, by way of Cheshire, Shropshire, and Staffordshire.

It would be beyond the scope of this book to attempt to trace out

[1] The exact limit is not accurately defined at present, and in North Derbyshire and Yorks there are areas that appear to have escaped glaciation (see p. 225).

[2] C. T. Trechmann, *Q.J.G.S.*, vol. lxxi, 1915, pp. 53–80.

the history of the different ice-dispersions.[1] Suffice it to say that it is abundantly proved that they reached their maxima at different times. In certain areas there were oscillations, sometimes one and sometimes another ice-stream holding sway, each leaving its record in the shape of distinctive erratics and striæ, by which the story has to be unravelled. It is, however, fairly certain that we are dealing with the products of more than one glacial episode; for in Europe and North America, both the contrast between the older and newer drifts, the presence of deposits with warm-climate fossils associated with others of glacial origin, and other considerations, show that there were within the Great Ice Age several alternations of glacial and interglacial episodes. If research should prove (and it is tending to do so) that during the interglacial phases Britain became virtually free from ice, it will become necessary to distinguish between the drifts of each epoch; and the problem of their interpretation will be even more complicated than it generally has been deemed to be.

Geographical Features due to the Glaciation

It is now proposed to discuss some of the more outstanding changes in the geography of Britain that are due directly to the glaciation. In the first place it will be noted that the glaciated region is divisible into (*a*) the uplands that were primarily regions of glacial erosion, and (*b*) the lowlands that were deeply mantled over by glacial deposition. The effect of the glaciation on the minor physical features and on the soil in the two regions is in great contrast. In the uplands the changes in the drainage and topography are generally ones of detail; and there are great expanses which the glaciers have swept bare of soil and subsoil, and which have not yet been sufficiently weathered for new soil to come into being. In the lowlands, on the other hand, there have been extensive changes in drainage and in the configuration of the country produced by deposition of the deep mantle of drift, which being itself barely consolidated, has weathered down to soil at the surface. Students of geography will at once recognize that the drifts have exerted an influence on the location of towns and on the types of agriculture, an influence based partly on the nature of the soil, partly on the water-supply, and occasionally on the defensive facilities of the topography.

Turning to larger changes due to the glaciation, attention must first be called to the direct increase in the land-area of the country which has resulted from the deposits. Lamplugh has shown (Fig. 96) that about one-eleventh of England and Wales would be flooded by the sea, were the glacial drifts removed.[2]

[1] See W. B. Wright, *The Quaternary Ice Age*, 1914, chap. iii.

[2] G. W. Lamplugh, *Proc. Geol. Soc.*, vol. lxxvi, 1920, p. lxvii.

River Diversions.—Changes, both small and great, in the courses of rivers are amongst the most remarkable effects of the glaciation. In many cases the position of the river channel has been altered without any considerable change in the general direction of drainage. For example, a pre-Glacial valley may have been nearly obliterated by glacial deposits, the surface configuration of which has, on the

FIG. 96.—Map of England to show the tracts (solid black) that would be submerged were the Drifts and later deposits removed.

Stipple, areas almost wholly overspread by Drift. Based on G. W. Lamplugh.

retreat of the ice, determined the course of the post-Glacial river that came to drain more or less the same catchment-basin. In such cases, as the stream has denuded the drift, it has usually recovered its original course, but on the other hand it has sometimes found itself cutting a new channel across what was a spur in the old valley (Fig. 97). The new course, once established, cannot be abandoned. Hence many post-Glacial rivers occupy courses that are partly re-excavated pre-Glacial valleys and partly new post-Glacial gorges. Along the Yorkshire coast also we frequently find two small streams occupying what was formerly a single valley. Here the drainage from the two sides has been separated by a plug of drift in the old valley-bottom, and erosion has not yet proceeded far enough to remove the barrier between the two streams (Fig. 97).

The Chester Dee.[1]—Reference has already been made to minor changes in the course of the Chester Dee near Llangollen. A few miles farther east a much larger alteration has been demonstrated (Fig. 98). From Llangollen eastwards for three miles to near Cefn the present river flows in its pre-Glacial valley, which is heavily

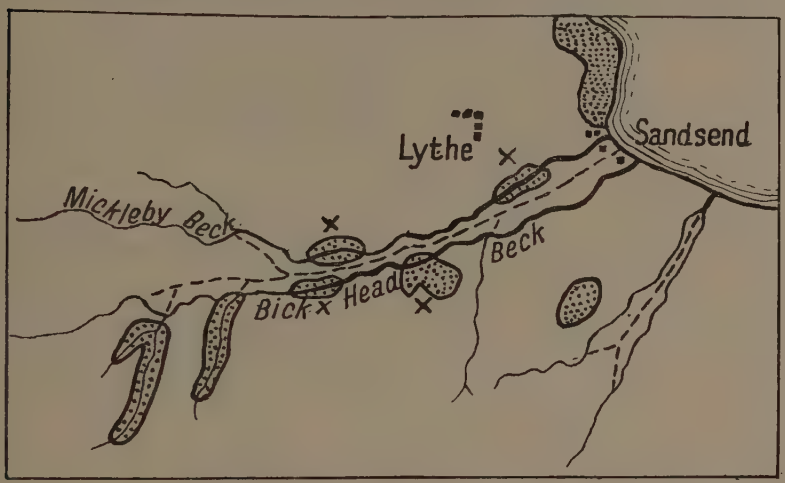


FIG. 97.—Part of N.E. Yorkshire to show relation of the present streams to the pre-Glacial drainage. Two pairs of brooks replacing single streams. At XX the Becks have met with pre-Glacial spurs, where they now traverse "solid" rocks.

Broken lines, pre-Glacial streams; stippling, "solid" rocks, here Jurassic; unstippled, Glacial Drift.

encumbered by drift; but east of Cefn it enters a long and deep gorge which has been cut in post-Glacial times. It emerges near Overton into the drift-filled pre-Glacial valley, but its old course is here buried by great thicknesses of boulder clay. It is possible to trace the abandoned valley from near Cefn, southwards to Chirk and Preesgweene; but it is not known how this middle course was connected with the lower one near Overton, for all the pre-Glacial topography is obliterated by a mantle of drift a hundred or more feet in thickness. It was the presence of this plug of drift in the former valley at Chirk that appears to have forced the river to abandon it at the point where it bent southwards near Cefn, and to follow a new and more direct, easterly course along the line of the present gorge.

Even this large change does not amount to a true *diversion*. By this term we imply that a river has been turned from its own drainage

[1] L. J. Wills, *Q.J.G.S.*, vol. lxviii, 1912, pp. 186–96.

basin into that of a neighbour. The case of Windermere and the river Leven has already been cited as a small example (p. 212). But

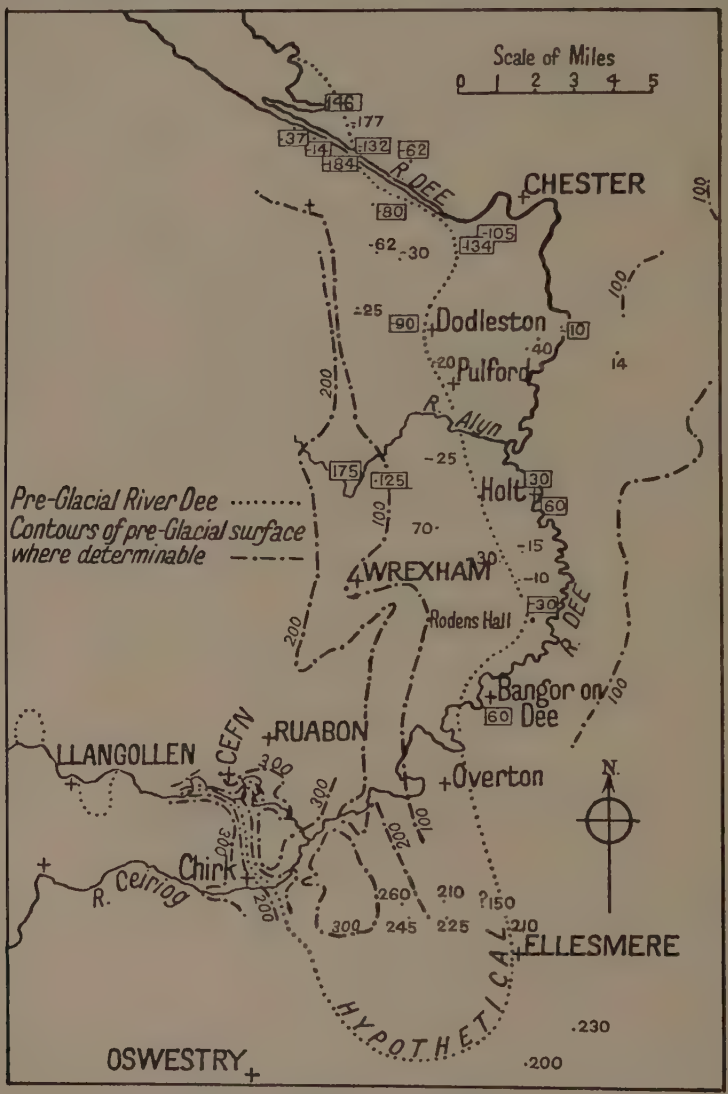


FIG. 98.—The Main Diversion of the River Dee. After Wills.
The figures give heights of the sub-Glacial surface above or below sea-level.

far vaster alterations have been demonstrated in the case of the Yorkshire Derwent and of the Severn, to which we may now refer.

The Yorkshire Derwent[1] (Fig. 99).—Prof. Kendall has shown that at one stage in the glaciation the Cleveland Hills were bare of ice, while in the Vale of York there lay a lobe of the Pennine glacier (Teesdale glacier), and on the north and east the great Scottish

FIG. 99.—Glacial Lake Pickering and the York Moraines.

Unglaciated area cross hatched; pre-Glacial drainage shown by dots and dashes; York Moraines in solid black, also the connecting osar-like ridge. Horizontal ruling, Glacial lakes. The South Yorkshire Lake was also held up by the ice to the east. Based on P. F. Kendall.

Northumbrian ice-sheet pressed inland. The latter prevented the Cleveland rivers from draining into the sea, and by the damming

[1] P. F. Kendall, "A System of Glacier-lakes in the Cleveland Hills," *Q.J.G.S.*, vol. lviii, 1902, pp. 471–571.

effect of its ice-front formed a series of lakes in the upper part of each valley (Fig. 99). Kendall traces out the history of the whole district, and shows how the water of one lake after another drained along the ice-front across each local watershed into the next river-basin, and eventually through the now-dry Newton Dale into a large sheet of water covering the Vale of Pickering (Fig. 99). The original drainage of this vale was eastwards to the sea between Scarborough and Filey, but the ice lay across the lower part of the valley so that the waters were impounded and rose until eventually they overflowed the western watershed near Kirkham Abbey, a possible lower outlet at Gilling being obstructed by the Vale of York ice-lobe. As the ice melted, a great dam of drift was left across the seaward end of the Vale of Pickering, and consequently the lowest outlet for Glacial Lake Pickering remained at Kirkham Abbey. Erosion of this outlet gradually drained the lake, so that the present course of the Derwent into the Humber is a true diversion.

The Severn[1].—The Severn and Vernwy flowing north-eastwards from the Welsh hills meet as they enter the Shropshire-Cheshire plain near Shrewsbury. Thence the Severn flows eastwards in meandering curves across the plain to Iron-Bridge, where it enters a deep gorge which continues with varying breadth past Bridgnorth to Bewdley, thereafter becoming less obviously a gorge. Even as far as Gloucester however the flood-plain of the river is deeply cut below the general level of the surrounding country.

If the map of the north-west Midlands be consulted (Fig. 100), the anomalous nature of this course will be apparent, for it will be seen that the Shropshire-Cheshire plains are surrounded, except at Iron-Bridge, and near Newport (Salop), by considerably higher ground to the west, south and east, and the natural outlet of their drainage is towards the Dee and Mersey estuaries, and not through Iron-Bridge.

The late Prof. C. Lapworth and Mr. F. W. Harmer independently suggested that in pre-Glacial times the Upper Severn flowed northwards to the Dee or Mersey, and that it became impounded into an ice-dammed lake by the advance of the Irish Sea Glacier southwards, counter to the natural drainage. No record survives of the lake formed during the advance, but similar conditions would have obtained during the retreat. On their view, as the ice melted the lake-waters rose until they drained out over the former watershed at Iron-Bridge. The rapid lowering of this overflow-channel led to the ultimate draining of the lake which was prevented from escaping to the Irish Sea, first by ice and later by the great deposits of drift that

[1] L. J. Wills, *Q.J.G.S.*, vol. lxxx, 1924, pp. 274–314, with references to former works.

encumber the Cheshire plains. There was a difficulty in accepting this view in that the gorge at Iron-Bridge cuts through the old water-

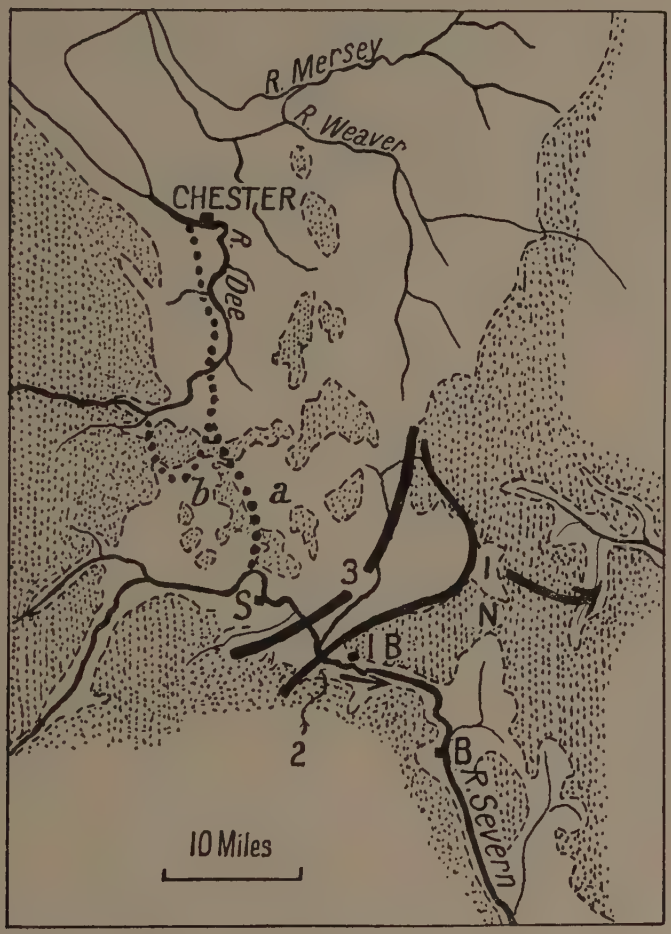


FIG. 100.—Diversion of the Lower Severn.

1, Lake Newport and the Gnossal to Church Eaton Brook overflow to the Trent. 2, Lake Buildwas and the Iron-Bridge Gorge overflow. 3, By the union of Lakes Newport and Buildwas, Lake Lapworth came into existence, draining by Iron-Bridge Gorge. The thick line 3, an early ice-stand at this stage. (*a*) Possible pre-Glacial course of the Severn. (*b*) Pre-Glacial course of the Dee. I.B., Iron-Bridge; S, Shrewsbury; B, Bridgnorth; N, Newport. Ground above 300 feet O.D., stippled.

shed where it is far higher than it is near Newport (Fig. 100 N). Harmer assumed that this Newport outlet was blocked by a lobe of

ice until that at Iron-Bridge had become established. The present writer in collaboration with E. E. L. Dixon has confirmed this assumption, and their work has also demonstrated the general truth of Lapworth and Harmer's hypothesis, but has shown that the Iron-Bridge gorge came to function as the outlet through a very complicated series of events.

CHAPTER XIX

QUATERNARY PERIOD (*cont.*): EARTH-MOVEMENT AND CLIMATIC CHANGES IN THE BRITISH EXTRA-GLACIAL AREA

Climatic Changes

Between the northern ice-sheets and the mighty Pleistocene glaciers of the Alps, which extended far beyond the confines of the mountains, there was a broad strip across Western and Central Europe that may be termed the extra-Glacial region (see Fig. 94). Here glaciers never formed, but during the Glacial episodes it was subjected to a rigorous climate that must have been completely arctic along its northern border. It has already been pointed out that alternations of glacial and more temperate inter-Glacial conditions took place during Pleistocene times; and these affected the extra-Glacial region (Fig. 108), increasing its area as the climate ameliorated, and vice versa. The southern and western counties of England, however, always lay within the extra-Glacial area, and for the greater part of the Pleistocene period were probably connected to the Continent.

It has been claimed by Nehring and others that in a general way the extra-Glacial region was divided physiographically into three belts running more or less parallel to the margin of the northern ice-sheets, namely:

a *Tundra Belt*, corresponding to a cold, sub-arctic climate;
a *Steppe Belt*, corresponding to a dry climate with a great annual range of temperature;
a *Forest Belt*, corresponding to a wet, probably temperate climate.

These belts are thought to have moved north or south with the oscillations of climate, so that a place situated in the Tundra Belt at a maximum of glaciation would, on the retreat of the ice, come to lie first in the Steppe, and later in the Forest Belt. Though this in general may be true in Central Europe, it is probable that in our own country, owing to its proximity to the ocean, forest succeeded tundra without a marked steppe-phase intervening.

The following pages set forth some of the evidence for the climatic changes that are recorded in the Pleistocene deposits of the extra-Glacial area in England.

a. Evidence of Cold, Subarctic Conditions.[1]

At the present day, these conditions give rise to *tundras*, such as those of Northern Siberia, which have been described as "boundless wastes of morass." Probably in most places underlain by frozen subsoils, they are treeless, mosses and lichens forming the prevailing vegetation. "In winter vast areas are covered with snow beneath which land, river, lake and morass are alike frostbound. With the advent of summer the coating of snow vanishes, and their surface-layer of soil is thawed out." Torrential floods occur in the rivers as the snow melts. A distinctive fauna and flora adapted to such conditions is found.

We may trace in Southern England many features and deposits that record the prevalence during the Glacial episodes of conditions approximating to those of the tundras. But the conditions were not quite the same as in Siberia, because of the proximity of the Atlantic, and because of the presence of the actual ice-sheets in the adjacent region to the north, so that on the one hand there was probably a heavier annual snowfall, and on the other hand there was a transition from tundras to an actual Glacial environment as the ice-sheets were approached These factors suggest comparison with present-day Alaska.

"The Head" or "Combe Rock."—Frost combined with abundant precipitation had the effect of deeply weathering the surface-

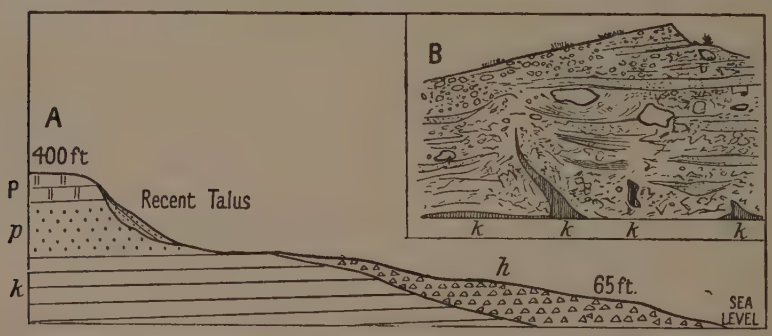


FIG. 101.

A. Section to true scale at Chesilton, Portland Island, to show relation of the "Head" (*h*) to the rocks from which it was derived. The material of the head is here chiefly Portland limestone and cherts which outcrop some distance to the south. Length of section 630 yards. P, Portland Limestone; *p*, Portland Sand; *k*, Kimmeridge Clay; *h*, head.

B. Section in the "Head" at same locality. Small and large blocks up to 10 ft. diameter of Portland limestone and chert with seams of Loess-like sand. In places Kimmeridge clay is squeezed up into the "Head." Both redrawn from J. Prestwich.

[1] The present tundra-belt has a low annual rainfall, but the ground is in summer wet owing to thaw above, and frozen ground below.

rocks into angular detritus which formed a mantle over a rock-zone that was frozen perennially to a considerable depth. In summer the melting of the snows produced great flows of mud, stones, ice and water, which appear to have given rise to barely stratified masses of angular or subangular fragments of all sizes, but mostly of local derivation, known as "*Head*," "*Combe Rock*," or "*Rubble-Drift*." Though usually found on the lower ground, this type of drift occurs at various heights and in positions where often it can not be related to any possible river-system. It differs from ordinary scree in the great distance to which it extends from the slopes on which the material was disintegrated, a feature indicating that the weathered rock was transported in times of thaw, when the whole surface became waterlogged and moved as a mud-stream (Fig. 101).

"Dry Valleys."—The perennial freezing of the subsoil had also a remarkable effect on the scenery of certain parts of this country, especially where permeable rocks like the Chalk (p. 199), the Bunter Sandstones, and the Permian Breccias form the surface. These formations frequently have their outcrops deeply dissected by "*dry valleys*," at present devoid of streams, but otherwise resembling normal river-valleys. The existence of these river-valleys where no river now runs, is best explained on the assumption that much of their excavation, especially of those of the Chalk country, took place under tundra-conditions in the Pleistocene; for if the subsoil were perennially frozen, these rocks would lose their permeability, and the thaw-water and the rainfall would run off at the surface. Probably also the greater precipitation under Glacial conditions would mean a higher water-table in the rocks, and that springs would be thrown out far above their present level, and in places that are now dry.

The "Terrace-gravels."—In Southern England the Thames through its northern tributaries was fed directly by the melt-waters of the ice-sheet, at any rate during the Glacial episodes. Not only the Thames, but all the other streams also in the extra-Glacial area were abundantly supplied with loose detritus (p. 31) which, despite its large size, could be transported by the great floods released during the summer-thaw. This is shown by the very extensive deposits of coarse gravels which we find in the form of terraces along the sides of all the main valleys (*terrace-gravels* [1]). In the terrace-gravels very large boulders occasionally are found. These were doubtless floated down on ice-rafts, such as are seen on present-day rivers that freeze over in the winter. The great irregularity often

[1] Other expanses of similar gravel that cap the plateaux of the Downs, Chilterns, etc., are termed "*plateau-gravels*." They usually cannot be related to any existing river, and in some cases are obviously of extreme antiquity. Some however are probably of Pleistocene age.

shown by the bedding and the lenticular nature of individual seams in the gravel point to its origin in turbulent floods.

The Fossils.—The present-day tundras support only a few, very specialized animals, many of which only visit them in the summer.

(*a*)

(*b*)

FIG. 102.—(*a*) Mammoth, engraved on wall of the Cave of Font-de-Gaume. (*b*) Rhinoceros, painting from same cave. Both after Breuil.

From Macalister, *Textbook of European Archæology*. Cambridge University Press.

Nehring gives the following as characteristic: the banded lemming, Siberian lemming, Arctic fox, variable hare, reindeer and musk-ox. During the extreme glaciation these same animals lived in Central Europe. Bones of lemmings have been discovered in caves and fissures in this country, and the reindeer and the musk-ox are

occasionally found in the river-gravels in Southern England, and may be regarded as evidence that at any rate at times during the Pleistocene tundra-conditions prevailed here. But in addition to these animals there were others, now extinct, that seem to have been adapted to somewhat similar conditions. The mammoth (*Elephas primigenius*) and the woolly rhinoceros (*R. tichorhinus*) are the most familiar of these. Carcasses of both have been discovered in the frozen soils of Siberia. One particular mammoth appears to have met a sudden death by falling into a morass, there to be put into cold storage until its recent discovery: in its stomach was found undigested grass and buttercups. Both mammoth and rhinoceros were clothed with long hair, a feature which is emphasized in the pictures that Palæolithic man drew of them (Fig. 102). Their remains are among the commonest relics of the fauna to be recorded from certain of our river-gravels (possibly because their great size attracts attention). Their presence is accepted as readily as that of the reindeer as an indication of arctic or subarctic conditions at the time of their fossilization. The flora of the arctic tundras is no less distinctive. It consists of mosses and lichens, together with diminutive shrubs, like the Dwarf Birch and Arctic Willow. The presence of these and other arctic plants in some of the peats associated with the river-gravels bears out the evidence of tundra-conditions supplied by the mammals.

b. Evidence of Steppe-conditions.

In continental regions of deficient rainfall away from the influence of the moisture-bearing westerly winds, the arctic tundras pass southwards into steppes, which are found at present in Russia and Siberia, and in the Canadian and American prairies. They are areas of scanty or seasonal rainfall with considerable extremes of temperature as between summer and winter. For these reasons they are natural grass-lands, for the rainfall is not sufficiently evenly distributed to allow of forest-growth. The steppes are characterized by a wind-carried dust-deposit known as *loess* (p. 41). The winds pick up dust in the dry season, often from areas outside the steppe-country itself; but there is enough vegetation in the steppes to entangle some of the dust, and thus prevent it from being swept away again. Hence arises an unstratified and very uniform clay having a marked tendency to vertical jointing, the latter feature being due to the dust being caught in the upright stems and roots of the grass. Being a wind-deposit, loess is not limited to the valley-bottoms, but occurs at all heights up to 8,000 feet. The steppes carry a special fauna, including jerboas, susliks, marmots, saiga-antelopes, wild horses and asses, and various mice and other rodents.

A general outward or anticyclonic movement of cold dry air appears to characterize the great ice-sheets of to-day, and there are reasons for believing that this was so in Pleistocene times. This implies that there would have been a tendency for a dry belt to be produced to the south of the tundras, and for the steppe-conditions of the central parts of the continent to invade the region to the west that would have been forested if the ice-sheets had not been in existence (Fig. 108).

This seems to have been the case, for loess was formed extensively in Central Europe and even in France, its origin under steppe-conditions being indicated by the presence in it of fossil representatives of the above-mentioned fauna and by its occurrence at varying levels on the valley-sides. In Britain, however, and to a large degree in France also, the climate was too oceanic for the formation of true loess, and in its place we find clays, known as *brick-earths*, occurring as the upper parts of some of the river-terrace deposits. The brick-earths may, like the loess, have derived their material from wind-blown dust (thus confirming the existence of steppe-conditions in adjoining regions); but their restriction to certain levels and their relation to the gravels show that they were laid down in flood-waters.

It seems reasonable to regard loess and brick-earths in Western Europe as indicating the transition from a glacial to interglacial climate or vice versa; but there is no palæontological evidence, except the widespread distribution of the horse and a single record of the saiga-antelope in the Thames Pleistocene deposits, to suggest a true steppe-climate in this country. Yet in the Midlands it can be shown that at some epoch or epochs in the Pleistocene, a dry enough climate obtained for wind-erosion to play a prominent part, for pebbles that have been deeply etched by a natural sand-blast commonly occur in the drifts and on the surface, and Dr. F. Raw has found rock-faces at Lilleshall and elsewhere that show the same feature. Since some of the wind-etched stones are erratics from Wales, it appears probable that the sand-blasting took place after the stones had been carried by ice to the Midlands, and therefore post-dates part at least of the Glacial period.

c. Evidence of Warm, Temperate Conditions.

1. In the Interglacial Episodes.—In the Alps there is much evidence to show that four glacial episodes were separated by three warmer interglacial phases in which the climate became at least as mild as at present. One would expect that such changes of climate would be recorded in the rest of Europe; but in our own country it would be unwise to claim that the Glacial sequence gives proof of the same four climatic oscillations. There is, however, evidence

that at times during the Pleistocene the conditions had so far improved that certain southern types of animals and temperate types of vegetation occurred in the same areas where at other times ice-sheets or tundras existed; and it is claimed that the fauna and flora belong to so mild a climate that the ice-sheets must have melted away, though valley-glaciers may have lingered on in the mountains. The evidence of the plants is mostly derived from certain peats found either below or between glacial deposits or occasionally in terrace-gravels. It is notable that the peats are not exclusively forest-peats, but contain the seeds of meadow plants as well as of forest trees.

The southern animals referred to above are usually found in river-gravels that, save in this respect, closely resemble those which yield the cold tundra-fauna; and it is clear that both faunas lived under conditions in which heavy-flooding of the rivers took place. The most characteristic southern forms were the straight-tusked *Elephas antiquus*, *Hippopotamus major*, *Rhinoceros mercki*, and the fresh-water shells *Unio littoralis* [1] and *Corbicula fluminalis*.[1] The large animals show African affinities, and were probably quite unable to face either tundra- or steppe-conditions.

The earliest undisputed flint-implements (Chellean culture) are found associated in gravels with this warm-climate fauna, and suggest that man made his appearance here under interglacial conditions.

2. In the post-Glacial Episode.—As the last relics of the ice-sheets were dwindling away, the country was elevated considerably, so that probably much of the continental shelf became land (see p. 239). This state of things is recorded in peat-deposits from both valleys and uplands, and in the submerged forests that occur round our coasts below sea-level. A study of the peat-deposits both in Scotland and Scandinavia has revealed changes in the type of vegetation, which are indicative of a changing climate during their formation. The plants found at certain levels in the peats and the presence of forest-peats themselves at heights above the present tree-line, show that since the last Glacial Episode our country has passed through a period with a more genial climate than at present. This climatic optimum is known as the "*Forest Period*" (p. 239), and was so recent that Man had arrived at the Neolithic cultural stage, and the animals were, with the exception of the Irish Elk, those that peopled the country at the dawn of history.

Changes of Sea-Level

The Pleistocene deposits record many instances of gentle up- and down-movements of large areas with respect to the present sea-level. It is more than probable that some of the changes may have

[1] Now found in Europe and Egypt respectively.

been *eustatic* (pp. 8, 243), i.e. due to alterations of the surface-level of the ocean. Subsidences of the sea-floor, the attraction of the sea-water towards the great mass of the ice-sheets, the abstraction of the water that was locked up in them, and its subsequent release, are all factors that may have governed the height to which the sea rose around our shores and, with the exception of the second, its level over the whole earth.

But it is also certain that gentle *isostatic* movements (pp. 6 and 8) of the crust have taken place over large areas in Northern Europe in both an upward and downward direction at different times during the Quaternary Period. The growth of a great ice-sheet with its enormous weight was sufficient to cause the crust on which it lay to sag downwards, while its disappearance led to a movement in the opposite direction. Upward and downward movements seem, however, to have occurred more or less contemporaneously in adjacent regions, suggesting that a sagging of the crust at one point cannot be effected without a displacement in the subjacent semi-plastic magma that produces an upward movement at another point.

At present we can rarely decide in any instance whether the movement registered in the various ways now to be discussed has been eustatic or isostatic, and in some cases it may be the resultant of the two. If we speak in the sequel of a submergence, subsidence or transgression we imply that the nett result of the movements has been an advance of the sea over the land. Such a movement is commonly said to be *positive*, a usage instituted by Suess. *Negative* movement on the other hand implies the retreat or regression of the sea, and the apparent uplift or emergence of the land (p. 241).

Let us now examine the data preserved to us from which such movements can be deduced to have taken place in the Pleistocene of the unglaciated region.

Effect of the Changes on the Coast-line.

Along the coast old beaches, sea-caves, and wave-cut platforms now raised above the reach of the waves, witness to positive movements while regression is recorded in submerged forests, drowned valleys, estuaries, and fjords.

(a) **Raised Beaches.**[1]—In a typical raised beach, as for instance the one illustrated in Fig. 103, a wave-cut platform of rock is found elevated above the level of the sea. It may terminate landwards in an old sea-cliff with wave-cut caves. Frequently on the platform and banked against the cliff lie the shingle and sand of the former sea-beach, now usually dissected, so that it is possible to examine its structure, its constituent pebbles and its fossil shells.

[1] W. B. Wright, *Quaternary Ice Age*, chaps. v, xv, xvi.

Round our coasts, raised beaches of various ages are found at heights ranging from a few feet to 130 feet above sea-level. In Sweden they are known to rise to over 900 feet (p. 239). Of the British examples the three best known are of particular interest.

(i) "*The pre-Glacial raised beach*" of Southern England, Northern France, and Ireland, is so called because it antedates part at least of the Glacial Period. It varies from sea-level in Yorkshire and the Isle of Man, to 25 or 30 feet above it in the south. Its pebbles include boulders of far-travelled erratics derived from stranded icebergs, indicative of the Glacial conditions to the northward; but the chief characteristic of the beach is that it is frequently buried beneath the

FIG. 103.—Raised Pre-Glacial platform of marine erosion, covered by gravels of 100-ft. beach, Islay. The foreground is the grassy platform of 25-ft. beach. To the right, present storm-beach of white quartzite shingle. (After photo by Geological Survey.)

Rubble-Drift or Head (see p. 230), which in turn at several places underlies Glacial drift, e.g. Gower and Ireland. Its uniformity in height shows that no *differential* movements of any magnitude have taken place since its formation within the area of its occurrence.

(ii) "*The Neolithic raised beach*" is also about 25 feet above sea-level. It is found in Scotland, North-East Ireland, and Northern England. The fact that it persistently overlies the submerged peat-beds of the "*Forest Period*" (p. 239) and that it contains flint and bone implements and canoes that prove it to be contemporaneous with Neolithic man, shows that it is one of the most recent marine deposits of our country. A similar beach is found at about the same level and with the same contents over wide areas in the Baltic Region (Beaches of the *Littorina* Sea). On its surface both in Denmark and Britain, are found piles of oyster and other shells, the "kitchen middens" left by the early Neolithic inhabitants.

The Neolithic beaches seem to have such wide distributions and to

occur at so constant a height, that one is almost tempted to regard them as records of eustatic changes in the level of the sea, their departure from horizontality being due to superimposed isostatic movements.

(iii) "*The* 100 *foot late-Glacial beach*" is only found in Scotland. It antedates the Neolithic beach that has just been described. Built up of coarse beach-gravel, it lies in places on a broad wave-cut platform (Fig. 103) about 100 feet above the present sea-level. Related to it, but at lower levels, we find contemporary marine clays that were deposited farther out to sea. These contain fairly deep-water arctic shells, and numerous boulders that must have dropped into the clay from drifting ice-floes. Here then are two very different types

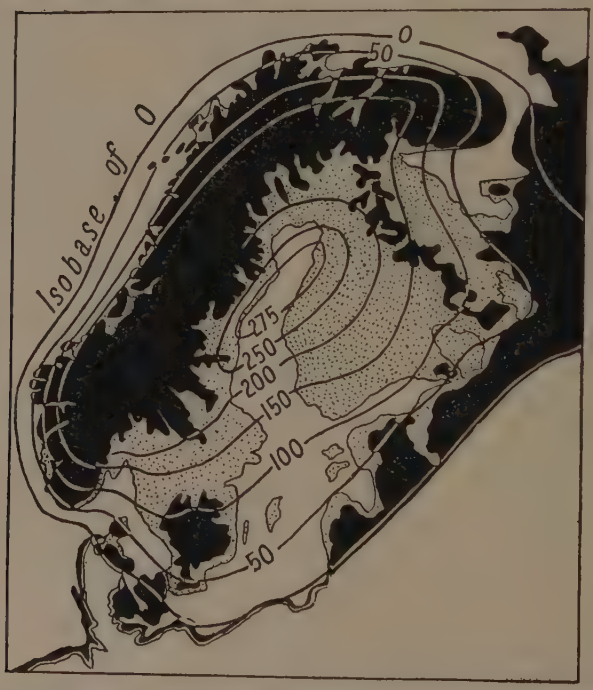


FIG. 104.—The isostatic depression of Fenno-Scandia, during the latest glaciation. Stippled areas, present land and lakes submerged by *Yoldia* Sea; full black within the isobase of O, land, then land; full black outside the isobase of O, parts of the present sea, then land. Based on Sederholm, W. B. Wright, and Munthe.

of deposits, the one marking the actual shore-line and the other registering a considerable depth of water, but both bearing witness to isostatic depression of the country under the vast load of ice that covered Scotland. The beach belongs to a late stage in the glaciation when the ice-sheets had dwindled to a series of valley-glaciers whose moraines are now found in so many of the Highland Glens.

The uplift that elevated the deposits to their present position, seems to have set in while the glaciers still occupied the valleys.

A similar but more perfect example of isostatic adjustment is the record of Glacial depression and post-Glacial elevation that has been worked out in Scandinavia. The nature of the movement is shown on the map (Fig. 104) by the use of isobases, which are lines joining adjacent points at which the land suffered the same amount of depression in Glacial times. It will be seen that the amount increases from a region peripheral to Fenno-Scandia (Scandinavia and Finland) towards Norrland and the Gulf of Bothnia. In post-Glacial times recovery to the corresponding amounts has taken place, so that in the central region the ancient beaches and marine clays are now as much as 900 feet above the level of the Baltic.

Something is known of the rate at which this elevation took place. De Geer has found a means of estimating the length of time since the front of the retreating ice-sheet rested along various lines in the Baltic region.[1] On his reckoning it is about 9,000 years since the ice stood at Stockholm, with its front melting in the sea. The elevation there has been 412 feet, or 1 foot in about 22 years. Corresponding figures at Ragunda in Jemtland, i.e. near the centre of maximum elevation, are 7,000 years and 750 feet, or a rise of 1 foot in say 9 years.

(b) Drowned Valleys and Submerged Forests.—While we have evidence in raised beaches and river-terraces that the sea once stood at a higher level relative to the land than at present, the occurrence of drowned river-valleys (estuaries, rias and fjords), buried river-channels, and submerged forests (represented by forest-peats), is proof that the reverse has also been the case. These proofs of emergence are found all round our coasts; and the movement may perhaps be regarded as *eustatic*. Borings in the Thames, Severn and other river-valleys prove that there are in each case ancient infilled channels 60 to 90 feet below the sea, a fact that demonstrates an emergence at least equal to that amount, and probably far greater.

This emergence took place during the so-called "Forest Period" (p. 235), the post-Glacial date of which is shown by the relation of the peats and the buried channels to Glacial deposits, and by the fauna and flora. It is of particular interest to realize that this elevation joined Ireland to Great Britain, and the latter to Europe at a comparatively recent date, and provided ground on which the post-Glacial fauna migrated into the British Isles from the Continent. This land finally was again submerged, so that the sea now stands at approximately its pre-Glacial level, and the lower parts of the valleys and the forest-peats in them have been carried beneath the sea, and buried under river and estuarine deposits (see Fig. 105).

[1] See W. B. Wright, *op. cit.*, p. 433, and De Geer, "A Geochronology of the last 12,000 years," *Comptes Rendus Geol. Congress*, Stockholm, 1910.

The Effects of the Changes on the Rivers.

The Pleistocene river-gravels (p. 231), now as a rule found as terraces [1] along the sides of the principal valleys, were laid down as flood-deposits when the rivers were flowing over flood-plains. The widening of a valley-bottom into a flood-plain by the lateral erosion and deposition of a meandering river (p. 27) is too well known to need an explanation here; but it is important to realize that the existence of a flood-plain implies that the river is graded, or, in other words, that a state of equilibrium has been attained between erosion and deposition with reference to some particular base, sometimes the level of a lake or of some resistant barrier across the valley, but in lowland valleys usually the level of the sea. This base governs the depth to which downward erosion can proceed, and thus controls the gradient of the river and of its flood-plain. Therefore these ancient flood-plain deposits are directly related to old sea-levels. It is clear that if the level of the sea be lowered, the river must become rejuvenated by reason of the increased gradient of its waters; downward corrasion will be renewed near the river-mouth, and be continued upstream until a fresh equilibrium related to the new base is attained.[2] If, on the other hand, the base is raised, as for instance by a positive movement of the sea-level, deposition at once sets in on a greater scale than before, and persists until the lower reaches of the river are silted up to accord with the new base. The gravels of a terrace may therefore represent simply a graded river, or, if they are of considerable thickness, they may imply a submergence of the land to an amount approximating to their thickness; and the presence of gravels terraced one above another records alternations of aggradation and excavation, related to alternations of submergence and elevation respectively.[3]

The gravels of the Thames illustrate the complexity of these phenomena during the Pleistocene. There are in the lower reaches conspicuous terraces at about 100 feet and 50 feet respectively above the present river (the 100-Foot or Boyn Hill and the 50-Foot or Taplow Terraces), and gravels and brick-earths known as the Flood-Plain Gravels which rise but little above the present alluvium. Finally alluvial deposits filling in the buried channel just discussed

[1] In some cases they underlie or occur at the same level as the present alluvium.

[2] If, however, the river flows into a shallow sea or estuary, uplift might merely extend the land seaward without appreciably affecting the river gradient. In such a case it seems probable that rejuvenation would not follow uplift.

[3] This statement has to be qualified by pointing out that rejuvenation of the river may also be produced by the differential uplift of its upper course or by a large increase in the volume of its waters. The gradient of a river also depends to some extent on the coarseness of the material it is transporting.

(p. 239), extend near the mouth to a depth of at least 90 feet below sea-level (Fig. 105).

The history of the Lower Thames as interpreted by the Geological

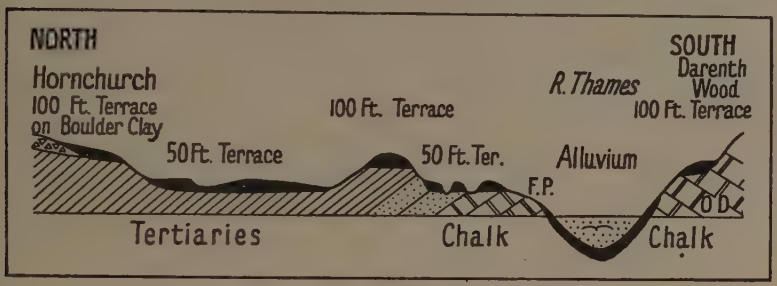


FIG. 105.—Section across Lower Thames Valley.

Full black, gravels. F.P. = Lower Flood-Plain gravels. 100-Foot Terrace or Boyn Hill Terrace; 50-Foot Terrace or Taplow Terrace. Length of section 9½ miles. Based on H. Dewey.

Survey is roughly as follows, beginning with the earliest events (Table VIII):

TABLE VIII

Amount and Direction of Movement of the Sea-level.	Result.
Negative	Excavation below the level of an ancient peneplain partly covered by "plateau-gravels" and boulder-clay.
Positive, 45 feet . .	Deposition of 100-Foot or Boyn Hill Terrace (at Swanscombe 44 feet thick).
Negative, at least 60 feet	Excavation of about 60 feet, below top of Boyn Hill Terrace.
Positive, perhaps 10–15 feet	Deposition of 50-Foot or Taplow Terrace until its surface was about 50 feet below top of the Boyn Hill Terrace.
Negative	Excavation.
Positive	Deposition of Upper Flood-Plain gravels, to about present flood-level.
Negative, at least 90 feet	Excavation of buried channel. The so-called "Forest Period" (p. 239).
Positive, 90 feet .	Deposition of Lower Flood-plain gravels and alluvium.

It will be noted that if this interpretation be correct, the gravels of the Lower Thames are arranged so that the lower the terrace the younger its age. Possibly future work may modify this view; for in the valleys of the Cam, the Warwickshire Avon, the Somme, and in the Upper Thames itself, the dating of the terraces by means of their contained fossils (including human artifacts in this term)

has led to rather different conclusions. We may examine the case of the Cam Valley (Fig. 106) where, according to Prof. Marr, the oldest gravels (1) lie near the present level of the river, but owing to submergence and aggradation the next younger (2) give rise to the highest terrace. Partial excavation followed by deposition, allowed the formation of newer gravels (4) on the eroded surface of (1). Finally a deep channel was cut and filled in by gravels (5) and recent alluvium.[1]

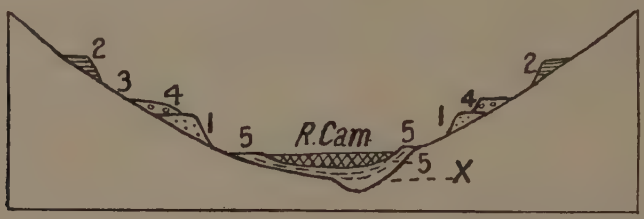


FIG. 106.—Section across Cam Valley, N. of Cambridge, with higher valley-slopes restored. The figures show the suggested order of formation of the deposits.

Cross-hatching, modern alluvium of Cam, 5. Barnwell Station Gravels (Upper Palæolithic 2), 4. Newer Barnwell Village Gravels (Upper Palæolithic 1), 3. Loams of Huntingdon Rd. area, 2. Observatory Gravels (Middle Palæolithic), 1. Older Barnwell Village Gravel and loam (Lower Palæolithic), X. Buried channel. Vertical scale greatly exaggerated. After J. E. Marr, *Proc. Cambridge Phil. Soc.*, vol. xix, 1917.

If this interpretation holds good, it follows that mere height above the river is no criterion of the age of a terrace when extensive aggradation has taken place, for a terrace may be carved out of the aggradation deposits at any level below their uppermost limits. Such a terrace records a pause in the uplift that followed the aggradation. Fig. 107 indicates how a low-level terrace may consist partly of very ancient deposits (1) and partly of recent ones (3), as in the Summertown-Radley terrace near Oxford described by K. S. Sandford,[2] and also shows how terraces at very similar levels may be made of gravels of quite different ages, as at X and Y. Not until the relative ages of the terraces have been established by means of fossils, can the changes of sea-level with which they are connected, be correctly determined. Our present purpose will, however, have been fulfilled if we have demonstrated that the river-valleys afford evidence of great oscillations of sea-level during Pleistocene times.

[1] J. E. Marr, "Submergence and Glacial Climates during the Accumulation of the Cambridgeshire Pleistocene Deposits," *Proc. Cambridge Phil. Soc.*, vol. xix, 1917, pp. 64–71, and *Q.J.G.S.*, vol. lxxv, 1919, pp. 204–229.

[2] K. S. Sandford, "The River-gravels of the Oxford District," *Q.J.G.S.*, vol. lxxx, 1924, pp. 113–79, and *Q.J.G.S.*, vol. lxxxi, 1925, pp. 62–86.

It would naturally be expected that some connection has been established between the river-terraces and the raised beaches in the extra-Glacial area; but it has to be confessed that little convincing correlation can so far be made. In the Somme Valley marine deposits connected with the so-called "25-foot pre-Glacial raised beach" (p. 237) are interbedded with river-deposits claimed to belong to the lowest or 10-m. Terrace. By analogy, the Flood Plain

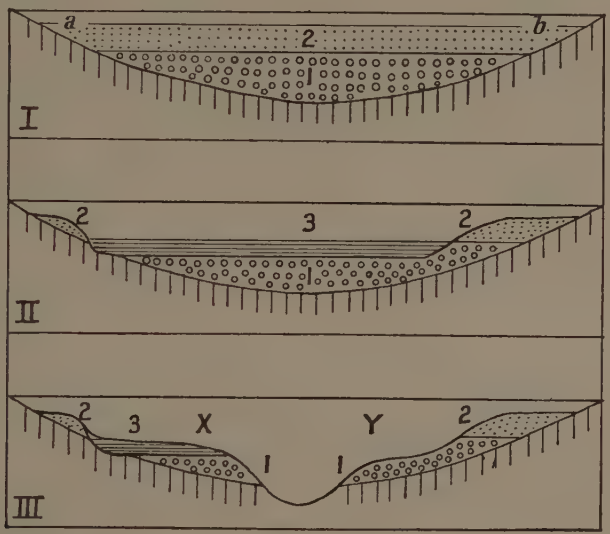


FIG. 107.—Diagram illustrating the formation of River-terraces.

I. Aggradation by deposition of 1 and 2 to upper limit *ab*. II. Pause in excavation with formation of a flood-plain and new deposits 3. III. Renewed excavation, and formation of a low terrace which at X is composed of 3 on 1, and at Y of 1. Note different sequence of terrace-deposits on the two sides of the valley.

gravels of the Thames may be contemporary with this beach, but little direct evidence is forthcoming. In Sussex [1] and near the mouth of the Somme [2] in France there is a raised beach at about 100 feet above sea-level (distinct from the 100-foot beach of Scotland referred to above) which some writers would correlate with the 100-foot terrace of the Thames and the third or 40-m. terrace of the Somme.[3]

[1] C. Reid, *Q.J.G.S.*, vol. xlviii, 1892, p. 344.

[2] C. Depéret, *op. cit.*, 1918, p. 3, and de Lamothe, *Comptes rendus Acad. Sci. Paris*, t. 162, p. 948, and *Bull. Soc. Géol., France*, ser. 4, vol. xviii, 1918, p. 3.

[3] Depéret claims that he can demonstrate great oscillations of sea-level in the Mediterranean (see p. 195), and he and his disciples have tried to show that these have affected the western sea-board of Europe and the English Channel, and that

Quaternary Man

The rapid alternations of level that can thus be demonstrated during Pleistocene times coincided with the most amazing changes of climate of which we have detailed records; and the conclusion seems almost inevitable that the two were closely connected. The combination of the two phenomena subjected the contemporary flora and fauna to a very severe trial of their powers of adaptability, for land disappeared and re-emerged from below the sea to the accompaniment sometimes of an Arctic, and at other times of a genial,

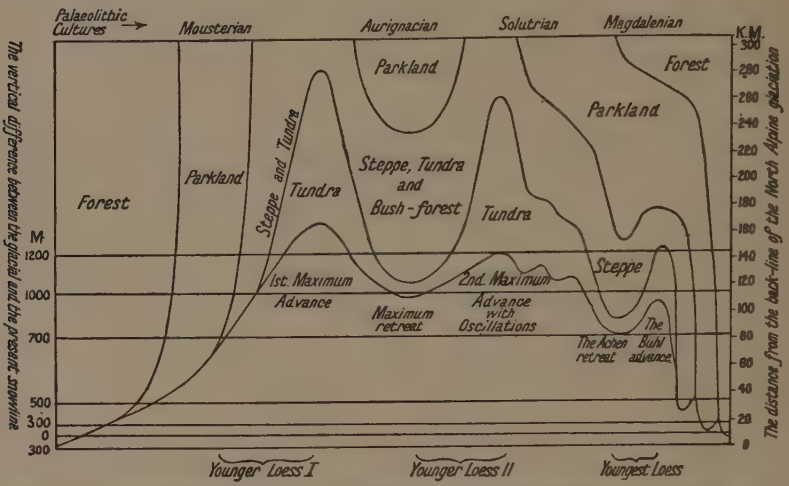


FIG. 108.—Glacial and interglacial migrations of Climatic Belts in South Germany. After Soergel.

climate (Fig. 108). The story of how the British fauna and flora of to-day was derived from the pre-Glacial ones, still remains to be told, for the geological evidence is obscure and the palæontological evidence very incomplete.

they are therefore eustatic. The limits of submergence in Depéret's four stages of the Pleistocene are stated to be as follows (in stratigraphical order):

4. Monastirian Stage	18–20 m.
3. Tyrrhenian Stage	28–30 m.
2. Milazzian Stage	55–60 m.
1. Sicilian Stage	90–100 m.

Depéret and his school see in the three great terraces of the Somme at 10, 30 and 40 m. above the present river, and in the Flood-Plain Gravels, the 50-foot and 100-foot Terraces of the Thames, evidence of rivers graded with reference to sea-levels closely corresponding with Nos. 4, 3 and 2 as set out above. Much work remains yet to be done before any such correlation can be regarded as proved.

To us the most interesting of the Pleistocene animals was **Man.** Gifted with the wonderful power to adapt himself to circumstances, he faced successfully both the rigour of the glacial and the keen competition of the interglacial episodes. We have only recently begun to know anything of his personal appearance; for very few skeletons have come down to us, though remains of his culture have long been recognized in the shape of tools [1] of stone and other substances, and though more recently great advances have been made in our knowledge of his artistry, as exemplified in his engravings, paintings and carvings (Fig. 102). Enough skulls and other bones have now, however, been unearthed to suggest that probably as far back as the earliest cultural stages more than one race of men inhabited Europe. Each race, as now, probably combined some distinctive cultural elements with others that were shared with its neighbours. This complicates the interpretation of the scanty record.

Remains of man's handiwork are usually preserved either in river-gravels into which they were washed or otherwise incorporated, or in the earthy and stalagmitic deposits of the caves which he inhabited. The application of the stratigraphical principle of the order of superposition to modern archæology has in the last half-century elucidated an ordered series of cultural stages in the working and shaping of flint and bone implements in Western Europe; and we are now in a position to be able to apply to the problem the second stratigraphical principle—the identification of strata by their fossil contents. For, with more than ordinarily stringent precautions, the cultural stage of the artifacts discovered may be used to tell us the geological age of the deposit that contains them.

The following are the chief cultural stages now generally recognized:

Iron Age Bronze Age Neolithic	Post-Glacial man.
Azilian Magdalenian Solutrian Aurignacian	Upper Palæolithic or newer Cave man.
Mousterian	Middle Palæolithic or older Cave man.
Acheulian Chellean Strepean	Lower Palæolithic or River-drift man.

[1] "Man is a Tool-using animal. Nowhere do you find him without Tools; without Tools he is nothing, with Tools he is all."—Carlyle in *Sartor Resartus.*

From a study of the animal remains associated with the different cultures, aided by the pictures made by man of the creatures he was familiar with, the following tenets seem fairly well established: (i) Chellean man lived in the open in a warm, probably interglacial, climate. (ii) Most of the Mousterian as well as the upper Palæolithic cultures appear to have coincided with one of the Glacial episodes when man dwelt chiefly in caves. (iii) Little agreement has yet been reached as to the correlation of the different Glacial episodes with the cultural stages.

With the ever-increasing tendency to apply strictly scientific methods to the study of Palæolithic archæology, there seems good hope of our recovering a history of how the human race under the hand of Providence came through the ordeal of the Glacial period, and how the trend of its evolution has been influenced by the varying environments to which it was then subjected. When that story is written, we shall have even more justification than now for being proud of these early men, our ancestors, who won through to better things, unvanquished by their surroundings.[1]

[1] The following may be consulted with reference to early man:
M. Boule, *Les Hommes fossiles*, English translation, Edinburgh, 1923. W. J. Sollas, *Ancient Hunters*, 3rd edit., London, 1924. M. C. Burkett, *Prehistory*, Cambridge, 1921. H. Obermaier, *Fossil Man in Spain*, 1924. R. A. S. Macalister, *A Textbook of European Archæology, vol. I, The Palæolithic Period*, Cambridge, 1921. D. A. E. Garrod, *The Upper Palæolithic Age in Britain*, Oxford, 1926.

PART III—THE PRE-CAMBRIAN AND PALÆOZOIC SYSTEMS

Introduction

Having been brought down to recent times in the preceding chapter, the reader will no doubt feel surprised to find the next one devoted to the most ancient rocks of all.

The justification for this arrangement has been given in Chapter I ; but it may be well to recall that the principal reason is to enable us to study first that part of the record which is simpler to interpret, before attempting to deal with the more ancient and more fragmentary record of the Pre-Cambrian and Palæozoic eras. Owing to the mutilated state of the evidence from which our knowledge of these early periods is derived and the vast lengths of time covered by them, a more generalized treatment has here to be adopted than in the previous part of the book, but each chapter aims at elucidating the processes of change appertaining to one or more physiographical environments, attention being focussed particularly on processes that have not so far been dealt with. Nevertheless, in order to bring out the essential continuity of the geographical evolution that produced these environments, a stratigraphical arrangement of the material is still adhered to, with the exception of Chapter XXV in which illustrations of volcanic processes are drawn from a variety of systems.

VI. PRE-CAMBRIAN ENVIRONMENTS

CHAPTER XX

THE PRE-CAMBRIAN RECORD

Nature of the Pre-Cambrian Record.—Various names have been suggested for the vast æon that elapsed between the formation of the first crust on the earth and the Cambrian period, when for the first time the remains of animals began to be preserved in the accumulating sediments in sufficient numbers to enable us now to recognize the rocks by means of their fossils. But for the purpose of this book the general term Pre-Cambrian seems most appropriate, in that it signifies merely that we are dealing with formations of

greater antiquity than the Cambrian. The Pre-Cambrian record is so complex that it does not lend itself to the treatment adopted in the rest of this book, and can therefore only be dealt with rather summarily.

Pre-Cambrian rocks can be grouped, broadly speaking, into two classes:

A. *Relatively unaltered rocks:*

1. Sedimentary. Mostly clastic rocks—conglomerates, sandstones, shales, occasionally limestones.
2. Volcanic Igneous. Lavas, ashes and agglomerates and small intrusions.
3. Plutonic Igneous. Vast intrusions, especially of granite, usually more or less gneissic, and then difficult to separate from metamorphic gneiss (below).

B. *Metamorphic rocks.*[1]

Slates, phyllites, schists, gneisses, granulites, mylonites. Both sedimentary and igneous rocks appear to have given rise to these, but the first three are perhaps more often of sedimentary origin. Gneisses often represent plutonic igneous rocks.

There are in various parts of the world, as for example in Canada and Finland, huge expanses of Pre-Cambrian rocks; but in our own country, the Hebrides and the Highlands of Scotland, and the north and west of Ireland are the only large areas floored by them. Elsewhere they occur as comparatively small inliers, peeping up from below more recent formations, and nearly every inlier presenting its own peculiarities. The more important occurrences are tabulated in Table IX, but the reader must consult other works for details of the stratigraphy.

In most regions where the Pre-Cambrian is largely developed it is possible to group the formation into:

2. *Proterozoic* or newer Pre-Cambrian.
1. *Archæozoic* or older Pre-Cambrian.

The Archæozoic mainly consists of very highly disturbed and metamorphic rocks whose structures indicate that they were acquired within the zone of flow, deep down in the crust. Plutonic and other intrusions are common and on a huge scale.

In the Proterozoic formations the metamorphism, if present at all, is generally of a lower grade; and it is often possible to recognize with certainty the original nature of the rocks. They are usually

[1] The reader is referred to p. 18, where the significance of metamorphism is briefly dealt with. See also G. W. Tyrrell, *Principles of Petrology*, Part III, London, 1926. C. R. Van Hise, "A Treatise on Metamorphism," *U.S. Geol. Surv. Monograph* 47, 1904.

separated from the Archæozoic below and from the Cambrian above by strongly-marked unconformities; but in some cases they appear to pass upwards without a break into the latter system.

TABLE IX

PRE-CAMBRIAN FORMATIONS

	Little Altered.	Metamorphic.
Hebrides and N.W. Highland Coast	Torridon Sandstone	Lewisian Gneiss
The rest of the Highlands and Counties Mayo and Donegal	. . . . .	Moinian and Dalradian Schists[1]
Anglesey	. . . . .	Mona Complex (schists and gneisses)
North Wales and South Wales	Pebidian (Volcanic with plutonic intrusions)	
Shropshire	Uriconian (Volcanic) Longmyndian (Sandstones and mudstones)	Rushton Schists
English Midlands . . .	Uriconian (Volcanic) Charnian (Sediments and volcanics)	Malvern Gneiss
Cornwall and Devon . .	. . . . .	Schists, etc.

Physiographical Processes in Pre-Cambrian Time.—For the student of past physiographies the most important question raised by the Pre-Cambrian record is whether the processes of change on and in the crust during that æon were the same as, or similar to, those that have held sway in later times and still function. In other words, does the uniformitarian principle (p. 1) apply to this æon? The following factors make it difficult to obtain an answer to this question:

1. The rocks formed during the Pre-Cambrian period though available for study over very large tracts in each of the continents, must underlie all the areas of Cambrian and later formations, and yet are precluded from examination in these areas.

2. As the formation of these rocks, whose bulk is enormous, embraced a period probably at least as long as the rest of geological time, it is clear that the stratigrapher is often faced with elucidating a very lengthy story from very imperfect materials.

3. Though it is often possible, by relying on the evidence of rock-

[1] Some authors regard these as possibly in part metamorphosed Lower Palæozoic rocks. Cf. A. Geikie, *Text-book of Geology*, vol. ii, 1894; G. Frodin, *Bull. Geol. Inst. Upsala*, vol. xviii, 1922, pp. 57 and 199.

facies, superposition, unconformities, igneous contacts, grade of metamorphism, etc., to establish the chronological sequence and something of the history of the Pre-Cambrian rocks of a particular district, yet their correlation from district to district is rarely free from doubt. This is due to the fact that correlation can only be based on lithology and other general considerations; for there are practically no fossils by which the members of one Pre-Cambrian formation can be identified and distinguished from those of another.

4. Vast earth-movements during Pre-Cambrian time have combined with all subsequent movements to mask the order of superposition and true relationship of formation to formation. In some cases though a sequence can be established, it remains doubtful whether it is inverted or not.

5. In most Pre-Cambrian rocks, owing to the changes wrought by metamorphism, it is far from easy to discover the original nature of the material, and accordingly it is still more difficult to reconstruct the physiographical environment in which the rocks came into being. Metamorphism in its extremest form has also led to the complete melting up of many parts of the Pre-Cambrian record, which are thus lost to us for ever.

Despite all the difficulties inherent in the study of the Pre-Cambrian, certain conclusions may be reached that bear on the question raised above, as to the applicability of the uniformitarian principle to the interpretation of the rocks of that æon. In the first place it seems possible that in the formative stages before the establishment of a cold and solid crust, the conditions were so different from to-day that we may expect no present-day terrestrial counterparts of the processes then prevailing. If, however, we limit our studies to the era after a solid crust with continents and oceans had developed, with an atmosphere and hydrosphere not greatly differing from those that have obtained in the Cambrian and more recent periods, it seems logical to assume that the processes of change were similar to those of later times, though they may have differed in degree and in the tempo at which they worked. This difference was most marked in the Archæozoic era.

Considering hypogene phenomena first, we note that in their high grade of metamorphism and in the amount of movement that they underwent in Pre-Cambrian times, the rocks of the Archæozoic [1] bear witness to a thinner, weaker, and hotter crust than has ever existed since. It is true that rocks affected by later orogenies may locally attain a similar grade of metamorphism (e.g. Lower Palæozoics in Scandinavia, p. 288); but regional metamorphism on the scale found in the Pre-Cambrian system seems rarely, if

[1] Excluding the formative eras.

ever, to have been reproduced in later ages, at any rate amongst rocks that can be examined at the surface.

Several great orogenies are known within the Pre-Cambrian æon, each accompanied by large scale plutonic intrusions and each comparable in magnitude with, if not exceeding, the better-known Caledonian, Altaid and Alpine orogenies.

When we turn to the volcanic and plutonic phenomena, it seems as if in the youth of the world vulcanism also may have operated on a grander scale than ever since. Not only do we find in almost any Pre-Cambrian region, wherever it be located on the face of the earth, thick formations of volcanic ashes and lavas, often recurring at intervals throughout a great thickness of rocks; but in nearly all regions where Pre-Cambrian rocks outcrop, there is in addition a multitude of igneous intrusions of every kind, some of which are of stupendous volume. These huge batholiths, laccoliths, and lit-par-lit injections are developed on a scale that can hardly be matched outside the Pre-Cambrian. Daly sums up his conclusions on this point as follows: "In brief, igneous action in all its principal phases peculiarly characterized the Pre-Cambrian era not only as regards persistence in time and wide extension in space, but also with respect to the scale of the magmatic movements." [1] As instances of the size of the plutonic intrusions he records seventeen batholiths in Labrador as covering 50,000 square miles (almost the area of England), while that of the Saguenoy District, Quebec, is itself 5,800 square miles in extent.

The products of vulcanicity were for the most part,[2] however, both chemically and mineralogically the same as those of more recent periods and of to-day, if we make allowances for the subsequent changes and metamorphism that they have undergone.

The *epigene* or *surface-phenomena* of the Pre-Cambrian period are recorded in the sedimentary rocks, and it is to these therefore that we must look for information about the composition of the atmosphere and of the sea and rivers, about the nature of the climate and of plant and animal life, and about the erosion and deposition that was in progress.

Atmosphere.—With regard to the composition of the atmosphere it seems clear that at the time when the first sediments were formed of which we have any relics, the constitution of the air was such that the surface waters acquired from it the supply of dissolved oxygen and carbonic acid requisite both for the chemical weathering of the rocks, and for the aquatic life of organisms.

[1] R. A. Daly, *Igneous Rocks and their Origins*, 1st edit., New York, 1914, p. 60.

[2] Daly, *op. cit.*, p. 58, states that anothosites are almost limited to Pre-Cambrian time, which was also in his opinion characterized by excessive development of true granites.

Life.—The oldest Pre-Cambrian rocks known in most of the areas that have been thoroughly explored are schists which were once sediments. This is, for example, the case in the North-West Highlands of Scotland where the "Fundamental Complex" consists of the metamorphosed sedimentary Loch Maree Series (mica-schists, graphite-schists, quartz-schists, jaspers, cherts and limestones) that have been invaded by the plutonic gneissic intrusions (Lewisian) that form the bulk of the Complex. The same is true in Canada, where the Laurentian granite-gneisses invade the Keewatin-Coutchiching sedimentary and volcanic formations. The presence in these early sediments of abundant graphite and occasionally of abundant limestones (now usually marbles) has been claimed by many as evidence that life existed in the Archæozoic. Graphite is regarded by these authors as the final product of the metamorphism of the carbonaceous matter of plants, and as it forms as much as 3 to 10 per cent by weight of some Archæozoic rocks, they cite it as evidence of abundance of lowly water-plants such as algæ (seaweeds) and floating micro-organisms; for it is highly improbable that the land surfaces away from the immediate vicinity of water were inhabited either by plants or by animals until perhaps Devonian times (see p. 305). On the other hand the argument is contraverted by other observers on the grounds that graphite may have been derived from carbon originally within the earth's crust.

The evidence of life afforded by the Archæozoic limestones is also somewhat indefinite. In most cases recrystallization has destroyed any direct evidence in the shape of fossils; though certain structures have been claimed to resemble the fibres of blue-green algæ. The fossil-like structure known as *Eozoon canadense* is not now accepted as a Protozoon animal, but it is thought perhaps to owe its peculiar banding to rhythmic precipitation resulting from the life processes of algæ. The whole structure is now crystalline as a result of metamorphism and may be entirely inorganic in origin.

In our country Archæozoic limestones are of insignificant proportions, but the Grenville Limestones of Ontario, usually referred to the Archæozoic, are said to be 50,000 feet thick! Daly has claimed the Pre-Cambrian limestones as chemical precipitates. Nevertheless he recognizes that organisms were probably present in the sea, for he states that in the absence of scavengers, the dead bodies would by their decay provide enough ammonium carbonate to precipitate all the lime salts dissolved in the water.[1] This complete precipitation of the lime is claimed by him to be the explanation of the absence of calcareous hard parts from the organisms of those

[1] R. A. Daly, *Bull. Geol. Soc. America*, vol. xx, 1909, and *Comp. rendus* XI *Congrès géol. internat.*, Stockholm, 1910, pp. 503–9.

days. Calcareous skeletons could only be acquired on his view after the ocean had received calcium salts in excess of the amount that could be precipitated through the decay of organisms. Various other explanations of the sudden appearance of fossils in the Cambrian have been put forward.[1]

To sum up, the evidence of life in the Archæozoic, though almost entirely indirect, is usually accepted as valid. Life was perhaps exclusively vegetable at first, but later consisted of both unicellular protophyta and protozoa.

In the Proterozoic the evidences of life are still found mainly in the limestones. Apart from the indirect evidence just discussed, there are the coral-like massive secretions of calcareous algæ (*Cryptozoon*) which occur as reef-like beds. Radiolaria, annelid tubes and trails, and the spicules of sponges have also been found. It is clear, however, that if there be any truth in the idea of evolution the skeletionless forerunners of the trilobites, brachiopods, molluscs, and, in fact, of all the main invertebrate groups, must have lived in the later Pre-Cambrian seas.[2]

The most striking evidence of the abundance of plant-life in the Proterozoic is found in the anthracitic coals (up to about 2 metres thick) in the Jatulian of Finland and Russia.[3]

The preceding paragraphs show that our knowledge of the life of Pre-Cambrian times is meagre, and that our views of the nature of the atmosphere and of the seas and rivers of the earlier periods, are based more on conjecture than on geological observations. What can we say then as to how denudation and deposition proceeded?

Denudation and Deposition.—Within the Archæozoic we know that at different times great earth-movements, to which reference has already been made, elevated the rocks into mountains which in turn were levelled, apparently by the usual agents of denudation into plains. Later these plains were covered by new sediments or by lava flows. This much can be argued from the unconformities which can still be detected.

Are we to assume that in the absence of terrestrial life weathering was mainly mechanical, or did the primitive atmosphere make good the deficiency in organic acids by providing other acids which to-day only form an insignificant part of the atmosphere and hydrosphere? Does the vast thickness of rocks eroded away in Archæozoic times

[1] Various papers, *Comp. rendus* XI *Congrès géol. internat.*, Stockholm, 1910, pp. 493–559.

[2] R. S. Lull in *Evolution of the Earth and its Inhabitants*, Newhaven, U.S.A., 1923, suggests in his diagram, Fig. 114, that the Vertebrates also had originated in the latest Pre-Cambrian times.

[3] J. J. Sederholm, *Comp. rendus* XI *Congrès géol.*, p. 516.

imply that the agents of denudation worked more quickly then than now, or are we merely dealing with unimaginable lengths of time? We can only guess at the answers to such questions.[1]

When, however, the sediments of the Proterozoic age are examined they are found to offer more positive data. They so closely resemble those of the Palæozoic and even more recent periods, that we are driven to the conclusion that, despite the general absence of fossils, the same agencies were at work in forming them, and that the surface conditions of the globe were not very unlike those that have since prevailed.

These views may be briefly illustrated by reference to the Torridonian System in the North-West Highlands of Scotland and to the Huronian of Canada.

We have in the Torridon Sandstone the remnants of a great pile (15–16,000 feet thick) of clastic sediments, prevalently red in colour, and varying from conglomerates, felspathic arkoses, and sandstones to fine shales. The formation extends from Skye to Cape Wrath. In most places the rocks have escaped the metamorphism that so usually obscures the original nature of the Pre-Cambrian rocks. The bedding is conspicuous, and as usual in coarse sediments false-bedding is often prevalent. The formation in its main outcrop has not been subjected to lateral compression and lies in many places practically horizontal. It has been deeply dissected by the erosion of the present mountains, so that the irregular unconformity between it and the underlying Lewisian gneisses can be readily studied (Fig. 116). These Archæozoic gneisses were originally deep-seated plutonic rocks, but they had been laid bare by prolonged erosion which had produced in Pre-Torridonian times a mountainous country with peaks at least 2,000 feet higher than the valley-floors. This —"the oldest landscape in Europe"—had obviously been moulded by the ordinary agents of terrestrial erosion, working, it is believed, under desert conditions in that there was probably no terrestrial vegetation, though the rainfall may not have been deficient. The sub-Torridon surface of the gneiss is often deeply weathered for some feet downwards. The valleys and peaks in the old landscape are alike buried beneath the red sandstones which seem to have accumulated in an inland sea or lake. The material of the sandstones is partly derived from the erosion of the ancient gneissic mountains, but in the main had its source outside the British Isles. This is evident from the composition of the sandstones which consist chiefly of grains of blue quartz and chips of fresh microcline felspar, for both of which no adequate source is known either in Britain or Scandinavia. It is supposed, therefore, that they were derived

[1] Pirsson and Schuchert, *Text-book of Geology*, Part II, 2nd edit., chaps. vii–xii.

from the desert-disintegration of granite-gneisses that now lie beneath the waters of the North Atlantic (see also p. 324).

The uneven surface on which the Torridon Sandstone lies denotes the submergence of a land-surface (Unconformity of Type 2, p. 65). At various levels, the beds of the Torridonian in contact with that land surface are conglomeratic, thus showing that throughout its accumulation local floods from time to time washed in the scree material that mantled the upper slopes of the hills, just as happens in semi-arid regions to-day (p. 84). Sometimes the pebbles are rounded by their water-travel, sometimes they are wind-cut and wind-polished. The red colour of the Torridon Sandstone and the abundance of unweathered felspar-grains in the arkoses also testify to the arid or semi-arid nature of the surrounding land. The rocks display in fact many features in common with the Trias, which we have already discussed as an example of a former desert-deposit (Chapter IX).

We may conclude, therefore, that the physiographical environment in which the Torridonian came into being was essentially similar to that found in semi-arid continental regions to-day.

Another interesting fact bearing on the question of the similarity of physiographic environment in those days to that found later, has been established in the Huronian System of Canada. Here Prof. Coleman [1] has discovered glacial deposits of Pre-Cambrian age which, with the exception that they are hardened and consolidated, are identical with those of the Pleistocene (p. 217). Large and small boulders bearing typical glacial striations are set in hardened clay (now slates). The deposit is an indurated boulder-clay and is known as *tillite*.

Associated with the tillites are laminated slates, strictly comparable save in hardness and cleavage with the "varv" clays of the Swedish Pleistocene (p. 218).

These glacial deposits [2] indicate that at any rate in one part of Proterozoic time the climate was cold and wet, and that the world probably then passed through at least one glacial epoch comparable with that of the Pleistocene.

[1] A. P. Coleman, *Ice Ages*, 1926.

[2] Supposed glacial deposits of Pre-Cambrian age have also been discovered in other parts of North America, Finland, and Australia.

VII. THE LOWER PALÆOZOIC GEOSYNCLINE AND THE CALEDONIAN OROGENY

The long cycle of Lower Palæozoic sedimentation in Britain furnishes us with an example of geosynclinal conditions, to be followed at the end of the era and in the Devonian by a grand orogeny, the effects of which are discussed in detail, as they appear to differ widely from those produced by the Alpine movements (Chapter XVI).

CHAPTER XXI

THE LOWER PALÆOZOIC SYSTEMS. A STUDY OF A GEOSYNCLINE

The Lower Palæozoic comprises three systems, the subdivisions of which are here tabulated:

Silurian	Salopian	Ludlow Series[1] / Wenlock Series	or	Denbighshire Series[2]
	Valentian	Tarannon[2]	or	Gala Series[2]
		Llandovery	or	Birkhill Series[2]
Ordovician	Ashgillian / Caradocian	Bala	or	Hartfell Series[2]
	Llandeilian		or	Glenkiln Series[2]
	Llanvirnian[2]			
	Arenician		or	Skiddaw Series[2]
Cambrian	Olenian / Paradoxidian / Olenellian			

These systems are represented in Britain and elsewhere exclusively by marine sediments and igneous rocks, the majority of the latter being of either submarine or insular volcanic origin. Of the lands of this era we know but little.

[1] The Downtonian is usually placed as the highest Silurian Series, but is here regarded as Devonian.

[2] Series primarily defined with reference to Graptolite Zones.

The rocks have as a rule been thoroughly compacted and indurated, and in general differ considerably in appearance from their equivalents in the more modern systems. They have also in most cases been profoundly affected by earth-movements which have produced both large-scale folds and dislocations, and small-scale crumpling and cleavage. Many of the finer-textured rocks are now slates. All these features add to the difficulty of investigating and interpreting the Lower Palæozoic formations.

We must also bear in mind that though these formations outcrop over large areas, especially in the Southern Uplands of Scotland, the Lake District, Wales, and North-East and South-East Ireland; yet over the rest of the country we know very little about them. They and the Pre-Cambrian below them probably form a rigid foundation below the greater part of Britain, though buried below a covering of newer rocks.

The length of time covered by the Lower Palæozoic era was so immense that by grouping together the three systems and treating them as one unit, we are attempting to generalize about events that covered a period probably at least as long as the combined Mesozoic and Cainozoic eras. In its vast duration one fauna after another came and went, and the earth crust repeatedly rose and sank, and sank and rose again. At this distance of time and from such mutilated materials, the reconstruction of the successive geographical environments must be a matter of extreme difficulty. The correlation of both strata and volcanic rocks that has been effected directly and indirectly by means of the fossils, has only now begun to show the contemporary conditions in various regions. Consequently it is only in broad outline that we can realize the physiographical factors that controlled the formation of the rocks.

Limits and General Characteristics of Lower Palæozoic.—The beginning of the Cambrian period was in this country, as indeed it was in most parts of the world where Cambrian rocks are found, a time in which a great transgression of the sea took place. The Pre-Cambrian formations had been folded and deeply eroded into an almost plane surface before they became submerged in this sea, in which the basal Cambrian sediments were laid down (Fig. 115). This is recorded in the great sub-Cambrian unconformity which is a fine example of an Unconformity of Type I (p. 65). As might be expected, therefore, the lowest [1] Cambrian sediments are neritic, but they are also distinguished from any that had preceded them by containing quite a large assemblage of fossils. The variety of creatures, and the high degree of organization and

[1] The very lowest are usually unfossiliferous quartzites, but pass up comformably into fossiliferous strata.

specialization they display, are convincing proofs that their ancestors must have thronged the Pre-Cambrian seas; but, as explained in the previous chapter, practically none of their remains have come down to us. The types of Trilobites, Brachiopods, and Pteropods which collectively form the bulk of the fauna in the lowermost Cambrian strata (Olenellus fauna) exhibit a remarkable similarity to one another in widely separated parts of the world. It seems as though the great extension of the sea that ushered in the Cambrian was accompanied by the almost world-wide dispersal of the earliest forms of life that had adopted protective and strengthening skeletons.

All the principal invertebrate groups appeared in the Cambrian; but throughout the Lower Palæozoic, Trilobites, Graptolites, Brachiopods, Molluscs, and Crinoids abounded, the first three being particularly useful in stratigraphical correlations.

The Lower Palæozoic era terminated at the end of the Silurian period with the general emergence of the Devonian continent and with the uprise of the great mountain ranges of the Caledonides (p. 272). The close of Lower Palæozoic times also coincided with the extinction of the Graptolites and the appearance of Fish in numbers.

Between the limits just discussed the Cambrian, Ordovician, and Silurian systems in Britain form a mighty pile of rocks, the accumulation of which represents a major cycle of sedimentation. Unlike the British Mesozoic cycle (pp. 165–9) which was completed in *epeiric* seas, that of the Lower Palæozoic was accomplished in a *geosyncline* (see below). We can recognize, especially in the Ordovician and Silurian two dominant facies amongst the sedimentary rocks. One is the bathyal, graptolitic facies that belonged to the deeper parts of the geosyncline. Typically it consists of black carbonaceous shale or slate with Graptolites as almost the only fossils, but in the Upper Silurian the facies may comprise grey silty shales and fine sandstones, yet here again with hardly any other fossils. The second is known as the Brachiopod-Trilobite facies and was essentially neritic in origin, having been formed around islands or on the shelving slopes of the continental areas bordering the geosyncline. The rocks of this facies may be conglomerates, grits, sandstones or shales, or occasionally coralline and other limestones. The fossils of the Brachiopod-Trilobite facies include in addition to these two classes, abundant Mollusca, Bryozoa, and Corals.

Since it is as an illustration of geosynclinal phenomena that it is proposed to view the records of the Lower Palæozoic, it will be appropriate to outline the present-day conception of a geosyncline.

The Geosyncline-Concept.[1]—Certain large areas of the earth's

[1] See E. Haug's *Traité*, chap. xii. J. W. Evans, *Q.J.G.S.*, vol. lxxxii, 1926, p. lx. The term geosyncline was coined in 1873 by J. D. Dana; the concept

crust have in the past been the scene of continuous sedimentation over long periods, a fact that implies the sagging of the crust as a large earth-downfold. Such a fold is a geosyncline, and the rocks that have accumulated in it are termed geosynclinal. There is no unanimity amongst geophysicists as to the cause of such a fold, and we shall not discuss this question here [1] (pp. 6 and 9).

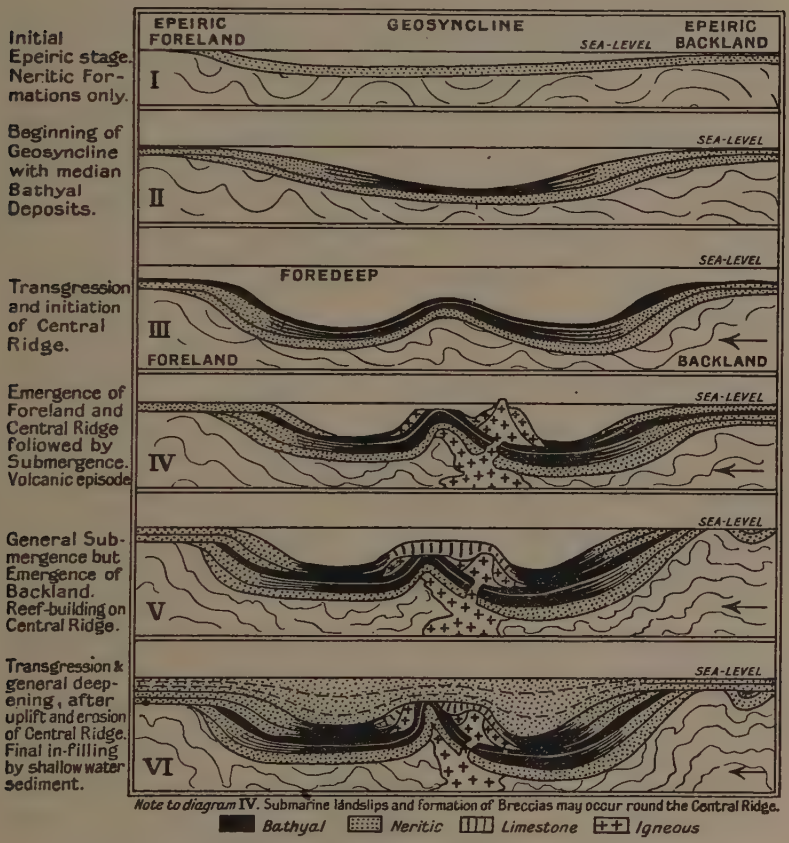


FIG. 109.—Diagram of the growth and filling up of a Geosyncline.

dates from James Hall in 1859, and has been elaborated by many others, notably Haug and the Swiss and French Alpine geologists.

[1] The reader is referred to J. W. Evans, *op. cit.* J. Barrell, in *Evolution of the Earth and of its Inhabitants*, Newhaven, U.S.A., 1923. H. Stille, *Senkungs-Sedimentations-u. Faltungsräume. C. R. Congr. géol. internat.* XI, Stockholm, 1910, pp. 819–36. C. Schuchert and L. V. Pirsson, *Textbook of Geol.*, Part II, 2nd edit., 1924, Chap X; and C. Schuchert, *Bull. Geol. Soc. Amer.*, vol. xxxiv, 1923, pp. 151–230, on American geosynclines. A. Holmes, *Geol. Mag.*, 1927, p. 263.

In the ideal case (Fig. 109) the deeper central parts of the geosyncline contains a full and unbroken series of strata, but towards the sides the effects of oscillatory movements are recorded by thinner sediments and by gaps in the sequence that are due to upward movement and erosion (p. 64), and by overlaps and transgressions resulting from renewed depression. The conditions in the centre are oceanic and bathyal [1] (p. 53), those to the sides are epeiric and neritic (p. 49). The latter are intimately bound up with the two continental masses which in typical cases [2] flank the geosyncline. These behave as hard rigid massifs, while the once equally rigid floor of the deeper part of the geosyncline is depressed to a level at which high temperatures and pressures tend to make the rocks plastic. We find therefore in the waning phases of the development of a geosyncline a great lens of unconsolidated new sediments overlying a semi-plastic crust of ancient rocks, while to either side lie rigid massifs of compressed and indurated formations which are merely veneered by a film of neritic strata (Fig. 74). Without going into the physics of the case, it is obvious that such an arrangement constitutes a zone of weakness if subjected to tangential (circumferential) compressive stresses. The geosynclinal concept envisages a tendency for the two continental masses to move relatively towards one another (see above, p. 184). At first this results (1) in the upfolding of parts of the sea-floor into submarine ridges and even into chains of islands, with trend-lines subparallel to the continental borders; (here, neritic deposits are formed, breccias reef-limestones, etc.); (2) in the setting up of volcanic and deep-seated igneous activity; (3) in transgressions or regressions of the sea across the continental borders.[3]

These features are illustrated diagrammatically in Figs. 109, 110, where the continuous nature of the bathyal deposits stands in strong contrast to the numerous unconformities in the neritic formations characterizing the central upfold and the epicontinental regions.

Once established, the anticlinal ridges tend to persist and as the compression of the geosyncline proceeds they form the major anticlinals of the new set of folds which arise. Finally there seems to

[1] Except around shoals and islands, see below.

[2] J. W. Evans has shown that many of the features of a typical geosyncline can occur on a continental slope covered with a thick blanket of sediment, without the intervention of a second continental land-mass (*op. cit.*, p. lxxvi).

[3] According to J. W. Evans, *Q.J.G.S.*, vol. lxxvii, such ridges and volcanic action may be primarily due to there being a less load of sediment towards the centre of the geosyncline. As a consequence an isostatic compensation takes place which expresses itself in an upfold, and is accompanied by the transference of magma and by concurrent vulcanicity. He also gives other reasons than the movement of the rigid massifs to account for the geosynclinal phenomena.

come a grand climax to the movement; the two continental masses are driven together, and the whole geosyncline between them is crushed. The yielding sediments together with slices of the ancient floor are piled one on another as a great mountain chain, such as has been described in the chapter on the Alps. The site of the geosyncline now becomes a geanticline. This sequence of events Haug claims as a general law which he states as follows: "Les chaînes des montaignes se forment sur l'emplacement des geosynclinaux." [1]

It may be seen from the foregoing brief description that the cycle of sedimentation in a geosyncline is intimately related to the movements and vulcanicity that both accompany its development and follow its completion. So much is this so, that the names that have been suggested for the parts of the geosynclinal system have reference to the surface direction which the subsequent orogenic movements have taken. Thus we distinguish as foreland and backland the two continental massifs, the former being the one towards which the main movement of the mountain-folding has travelled (see Fig. 78).[2] The foredeep is the ocean depth adjoining the foreland. In the diagram (Fig. 109) it is shown as separated from a second deep by an upfold. The reader should also refer to Fig. 82, p. 184.

The Lower Palæozoic Geosyncline in Britain

Having seen the general characteristics of a geosyncline, we may anticipate by stating that in the case under review (Fig. 110) the foreland was a northern continent, sometimes referred to as Atlantis, of which we see fragments in the Outer Hebrides and the North-West Highlands. The foredeep lay over Scotland, the Lake District, and Northern Ireland, and trended north-east, parallel to the northern continental edge. A second deep, at times closely connected with the foredeep, can be traced through North Wales and South-East Ireland. In the deeps there arose at different times islands, some volcanic, others due to the upfolding of the sea-floor. The backland can be recognized with less certainty. Part of it may have lain over the midland and southern counties and North France, with much of its continental shelf often below water, but the Baltic shield and the Russian Platform probably formed the major part of the rigid block that acted as the backland. The mountain-ranges

[1] Haug, *Traité*, vol. i, p. 160.

[2] According to Kober in a typical orogen the foreland and backland occupy reciprocal positions with respect to both the geosyncline and the orogenic systems (see Fig. 77, p. 180); and cannot be distinguished, since they are both forelands with respect to the superficial direction of movement on the two sides of the system (see also p. 179).

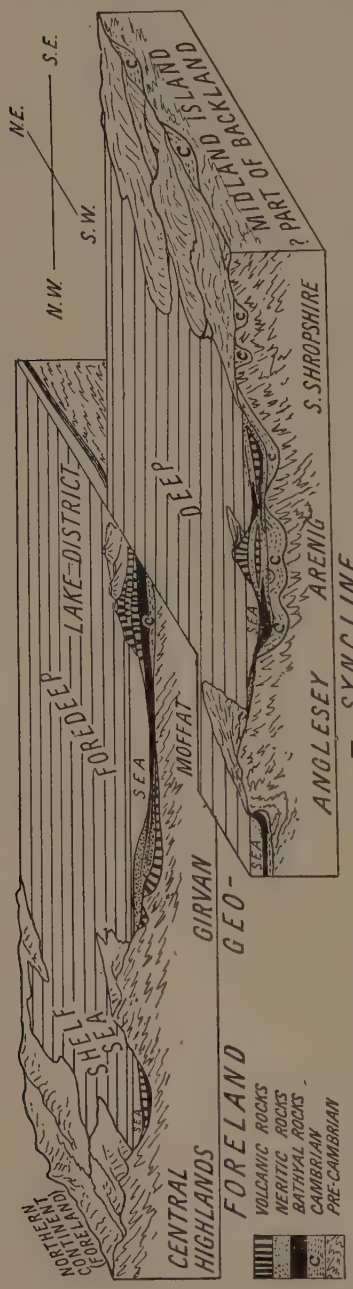


FIG. 110.—Block Diagram, illustrating the Ordovician Geosyncline in Llandeilo times.
Solid black, bathyal; stippled, neritic; transverse lines, volcanic; C, Cambrian.

that were built from the geosyncline were the Caledonides or Caledonian Chains, the usual trend of which is north-east, but north-north-east in the north-west of Scotland (Fig. 114). The earliest signs of folding can be detected at the end of the Cambrian period, but the principal movements began in late Silurian times and culminated in the Devonian.

The development of the geosyncline [1] may be traced through three stages.

i. Cambrian.

The general picture that we get of Lower and Middle Cambrian times is of a shallow, but widespread, epeiric sea that had recently flooded a large continent. There was at first an abundance of sandy sediment, now converted to quartzites; here and there strong currents carrying coarser material laid down grits and conglomerates, and elsewhere by erosion of the sea-floor produced non-sequences (e.g. at Comley [2]).

[1] W. G. Fearnsides, "North and Central Wales," *Geology in the Field*, chap. xxxii. O. T. Jones, *Q.J.G.S.*, vol. lxxvii, 1921, pp. 144–74.

[2] E. S. Cobbold, *Q.J.G.S.*, vol. lxxvi, 1921, pp. 325–86; also at Nuneaton, Warwickshire, C. V. Illing, *Q.J.G.S.*, vol. lxxi, 1915, pp. 386–450, and in Sweden.

In yet other places quieter and muddier sea-floors were to be found. The transgressive nature of the base (p. 63) is well displayed in the North-West Highlands where the basal quartzites lie on an even surface of marine erosion cut in the Torridonian and Lewisian (Fig. 115), so even, in fact, that it is clear that the underlying platform of Pre-Cambrian rocks had already acquired a high degree of stability (see also Fig. 116).

In the Middle and Upper Cambrian stages we catch the first definite glimpses of the Lower Palæozoic Geosyncline. Almost everywhere from the Lake District and the Isle of Man, across Wales, Shropshire and the Midlands, deeper-water conditions are evidenced by the predominantly shaly facies found in the Upper Cambrian. The Lake District and Isle of Man developments (Skiddaw and Manx States) are mainly dark, barren or graptolitic slates, which appear to have originated under much the same conditions as the black graptolitic shales of the Ordovician of the Southern Uplands, which it will be shown later (p. 266) can be regarded as the sediments of the foredeep of the geosyncline. To the north in the Highlands, clear but fairly shallow-water conditions are indicated by the Durness Limestone, which is partly of Cambrian and partly of Ordovician age. Here also the general subsidence is evidenced by the great thickness (1,500 feet) of what has been regarded by some as reef-limestone. It is found that the fossils of the Durness Limestone have little in common with those of the Cambrian of North Wales and the Midlands. Geographically the bathyal[1] Skiddaw Slates lie between the two neritic facies; and it is believed that the deep water of an ocean trough prevented the mingling of the two faunas.[2] The direction of the ancient continental shelves seem to have been more or less east and west or east-north-east and west-south-west; for we can match the "northern" or Durness Limestone fauna closely in North Newfoundland and Quebec, while the "southern" or Welsh fauna extends from the Appalachians and New York through Southern Newfoundland and Southern Britain to Sweden.[3] The faunas were, it seems, free to migrate along the continental shelves but quite unable to

[1] It would perhaps be better to label the Skiddaw Slates as *geosynclinal* rather than *bathyal*, as the shale-facies is associated with grits and sandstones. In this respect compare with the neritic breccias, etc., of the island-festoons of Tethys, p. 186.

[2] The separation might perhaps be due to poisonous bottom-waters, see p. 269.

[3] The peculiarity of this arrangement on the two sides of the Atlantic is a strong argument in favour of Wegener's theory of the separation of the two continents by drift, though the case is not mentioned by him in his analysis of the correspondence in structure of Eastern America and Western Europe. See also E. B. Bailey, *Brit. Assoc. Rep.*, 1928.

pass freely across the intervening deep sea (Fig. 111). The contrast is so great, however, that a land-barrier has often been postulated to separate the two faunas.[1]

The remarkable persistence of the lithological characters of the quartzites, shales and limestones constituting the three subdivisions of the North-West Highland Cambrian for a hundred miles along

FIG. 111.—The interrelationship of Geosyncline and Mountain-building.

The Lower Palæozoic Geosyncline in Cambrian times, shaded. The Caledonian mountain-chains, full black. Based on Koch, Bailey, Schuchert, Poulsen, Stamp.

the strike in a north-north-east direction has been adduced by Peach and Horne as evidence that in each case the formation as now seen along the outcrop was laid down at a constant distance from the old shore-line. This they therefore regard as having followed a north-north-east direction in that region.

ii. Ordovician and Lower Valentian.

In the North-West Highlands and in the Lake District there was no striking change of environment at the end of the Cambrian

[1] See Schuchert's reconstructions, and O. Holtedahl, *Amer. Journ. Sci.*, 4th ser., vol. xlix, 1920, pp. 1–25. C. Poulsen, *Jubilaums exped. Nord om Grönland*, 1920–1923, No. 2, 1927. (*Saertryk af Meddelselser om Grönland*, lxx.)

period, for the same facies continued to be deposited in Lower Ordovician times. Farther south, however, the end of the period coincided with the first signs of the Caledonian earth-creep. Certain areas of the sea-floor, as for example the north-western part of Wales (including Anglesey), and perhaps Pembrokeshire and Shropshire, were elevated and brought under the influence of erosion. This is evidenced by the unconformable base of the Ordovician which rests upon various members of the Cambrian and even upon the Pre-Cambrian in Anglesey.[1]

The Anglesey ridge seems for a long time to have divided the geosyncline into the northern deep and the southern deep, referred to above on p. 261. (See also Fig. 110.)

At about the same time the first great volcanic eruptions took place, the products of which are the andesitic lavas and agglomerates of Rhobell Fawr. This volcano appears to have been sometimes submarine and at other times subaerial.[2] Roughly contemporaneous are the andesites of Trefgarn in Pembrokeshire.[3]

It is not known whether the Midlands, from the Longmynd south-eastwards, were elevated into land at this time, but it does seem as if this region as far south as the Bristol Channel was a continental massif which, throughout the Ordovician and early Silurian periods[4] bounded the Welsh geosyncline on the south and east. At times the sea advanced on to it (e.g. Caradocian of Church Stretton), but it was not entirely submerged until Upper Valentian and Salopian times.

The shallow-water Ordovician sediments round Girvan in Ayrshire, and again in County Mayo, demonstrate that the northern land-mass had now been extended, at any rate in places, farther south than in Cambrian times. This may indicate an early phase in the folding of the Caledonian ranges of the Highlands which afterwards found their maximum development in this region (Fig. 110).

We see then that in general the Ordovician and early Silurian geography differed from the Cambrian chiefly as follows: (i) the coastal regions of the geosyncline approached one another more closely; (ii) there was probably a large land-mass defining its south-eastern side. Perhaps this had a N.E.–S.W. coast-line.

In the main geosyncline which lay between the north of Ireland and the Highlands on the one hand and the Midlands on the other, the floor of the sea in general continued to subside, thus allowing a vast pile of sediments to accumulate in the regions bordering the

[1] E. Greenly, "Geology of Anglesey," *Mem. Geol. Surv.*, 1919, vol. ii, p. 241.
[2] A. K. Wells, *Q.J.G.S.*, vol. lxxxi, 1925, p. 426.
[3] H. H. Thomas and A. H. Cox, *Q.J.G.S.*, vol. lxxx, 1924, p. 546.
[4] W. B. R. King, *Q.J.G.S.*, vol. lxxxiv, 1928, pp. 694–7.

coasts of the land-massifs and of islands and shoals, many of which were volcanic. In the intervening areas quite thin deposits of black shale record the slow sedimentation characteristic of deep water. In some places very puzzling rapid changes of composition and thickness are found as a result of this arrangement, the thin black bathyal [1] muds (now shale or slates) with Graptolites (p. 258) replacing in a short distance a thick contemporaneous series of detrital or pyroclastic rocks with a Brachiopod-Trilobite fauna (p. 258).

The classical example of this is the strongly contrasted sequences in the Moffat and Girvan districts of South Scotland (Fig. 112). These are set out in Table X.

TABLE X

THE CONTRAST BETWEEN THE NERITIC FACIES OF GIRVAN AND THE BATHYAL FACIES OF MOFFAT [2] (Fig. 112).

	Girvan District.	Moffat District.
Valentian	*Lower Valentian* . 1,000 feet Sandstones and limestone with trilobites and brachiopods.	*Birkhill Shales* . . 140 feet Soft black shales divisible into six graptolite zones.
Bala	*Ardmillan Series* . 2,600 feet Grits, sandstones, flags, and shales, with black shales at intervals; four Hartfell graptolite zones recognized.	*Hartfell Shales* . . 100 feet Black shales divisible into five graptolite zones.
Llandeilo and Llanvirn	*Barr Series* . . 800 feet Conglomerates, sandstones and shales. One Glenkiln graptolite zone recognized. Unconformity here.	*Glenkiln Shales* . . 50 feet Black shales divisible into two graptolite zones.
Arenig	*Arenig Series* . . 1,570 feet Cherts and black shales above some 1,500 feet of lavas, tuffs and thin shales.	Mudstones, shales, and cherts 150–200 feet Tuffs . . . (150 feet seen).

The sediments of the former belonged to the central and deeper part of the geosyncline and are essentially bathyal (p. 54) in that they show a continuous sequence of sediments laid down on a current-

[1] It is clear that much of the geosyncline was covered by neritic deposits, and even the black graptolite shales are not necessarily bathyal (see p. 269, and W. B. R. King, *Q.J.G.S.*, vol. lxxix, 1923, p. 493).

[2] See C. Lapworth, *Q.J.G.S.*, vol. xxxiv, p. 240; vol. xxxviii, p. 587, and B. N. Peach and J. Horne, "Silurian Rocks of Britain, vol. i, Scotland," *Mem. Geol. Surv.*, 1899.

free bottom sufficiently far from a source of detritus for the deposits to be exceedingly thin. The fossils are Graptolites, pseudoplanktonic creatures that lived in the surface water and were probably attached to floating seaweeds. They were distributed far and wide as the weeds drifted with the currents, and as both weed and Graptolite died they sank together to the bottom. Where there was but little detritus as in the regions far from the shore, the carbonaceous matter of the plants was in sufficient bulk to give the dark colour to the black mudstones [1] in which the Graptolites are typically found.

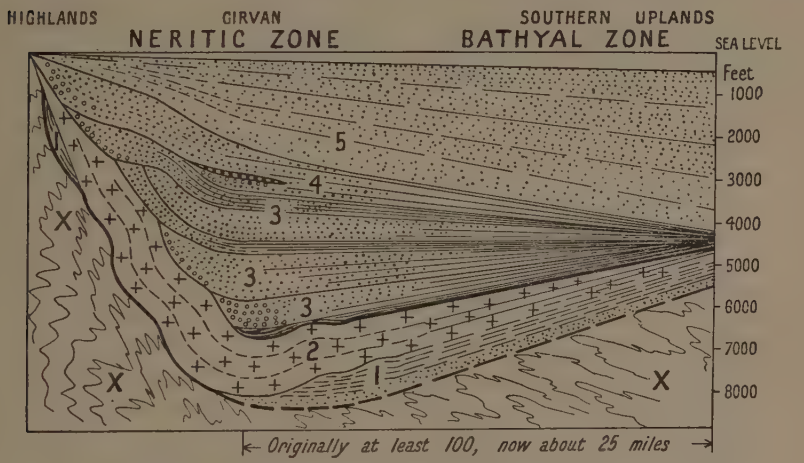


FIG. 112.—Diagrammatic section of the Caledonian Foredeep at the end of Valentian times.

1, ? Cambrian. 2, Arenig. 3, Llandeilo-Bala. 4, Lower Valentian. 5, Upper Valentian. X, Pre-Cambrian. Stipple, neritic; full black, bathyal shales; × ×, volcanic.

Nearer to land the amount of detritus masked this effect; and the rocks took on a grey or buff colour, and Graptolites were only occasionally preserved, their place being taken by the benthonic forms like Trilobites, Brachiopods, Bryozoans, and Corals.

The uniformity of facies in the black mudstones of the Moffat Ordovician records a corresponding uniformity of environment, that of the surface-waters of the open ocean. Accordingly the changes observed in the Graptolites, as we pass from one bed to the next above, are changes due to evolution, and not to varying environment. A standard sequence of graptolite zones can therefore be established on an evolutionary basis, as was recognized and proved by the genius of the late Prof. Charles Lapworth despite the extraordinarily disturbed nature of the deposits.

[1] Iron pyrites in some cases contribute to the dark colour.

The correlation of the contemporary deposits of the Girvan district was effected by Lapworth chiefly by means of the Graptolites which are found in thin bands of shale intercalated among the coarser sediments. By adopting the Moffat graptolite zones as a standard, he proved the 4,400 feet of sediments at Girvan to be the time-equivalents of the 290 feet of shale at Moffat (Llanvirn to Lower Valentian). The Girvan sediments were laid down along the northern border of the geosyncline on the continental shelf of the foreland, their materials being largely derived from that source. The rocks are as typically neritic as the Moffat ones are bathyal. The conglomerates and sandstones, and possibly also the limestones, betoken coastal conditions. The unconformities and gaps represent times of slight elevation either above sea-level or into the region of effective submarine current-erosion (Fig. 112). The occasional thin bands of black graptolite shale that are so invaluable in correlating with Moffat show that at times the coast-line receded and the sea deepened sufficiently for bathyal conditions temporarily to invade the region.

Vulcanism.—It has been pointed out above that vulcanism usually accompanies the movements connected with a geosyncline. This is strikingly illustrated in the Ordovician.

We are not here concerned with the detailed stratigraphy of the volcanic rocks; but it may be noted that they occur in different districts at a variety of horizons from pre-Arenig times (p. 265) right through the Ordovician.[1] We may mention Cornwall; Pembrokeshire; Brecknockshire; Radnorshire; Montgomeryshire; Shropshire; the Berwyns, Cader-Idris, the Arans, the Arenigs and Snowdonia in North Wales; the Lake District; Southern Uplands; Dublin, Kildare and Mayo in Ireland. In fact so widely distributed are the lavas and ashes that we must think of the Ordovician sea as having been thickly studded with volcanoes. Some poured forth lava, the submarine origin of which is shown by its curious form that has been likened to a pile of sacks or pillows (Fig. 141, in which, however, the lava is not of Ordovician age). These are the so-called "pillow-lavas" (p. 16). The fairly deep-water origin of the Ordovician pillow-lavas is indicated by their association with radiolarian cherts[2] and black graptolitic shales, both of which are rock-types demanding a general absence of terrigenous detritus from the sea-floor during their formation. We may conclude,

[1] The last traces of this vulcanicity are seen in the Silurian of Gloucestershire.

[2] Secondary silica, possibly derived from volcanic emanation, may have contributed to the formation of the chert. H. Dewey and J. S. Flett, *Geol. Mag.*, 1911, pp. 201 and 241. C. I. Gardner and S. H. Reynolds, *Q.J.G.S.*, vol. lxviii, 1912, p. 80.

therefore, that the pillow-lava volcanoes broke out on the sea-floor away from the coasts and never reached sea-level.

There were however others, such as those of Arenig and Snowdonia, which, though at times probably submarine, rose at other times above the sea as subaerial cones, possibly of the Vesuvian type. These volcanoes emitted not only lavas, but vast beds of agglomerate, ashes, and tuff, some of which, in that they are fossiliferous, were clearly formed on the sea-floor.

Associated with the volcanic rocks, it is usual to find in North Wales and in the Lake District, intrusive igneous bodies of various sizes, many of which belong to the same cycle of igneous activity. Both intrusive and extrusive rocks are alike expressions of the crustal changes which were going on and which demanded compensating adjustments in the potentially liquid substratum. We note in this connection that many of the lavas and tuffs are members of the so-called "*Spilitic*" suite of soda-rich igneous rocks, which has come to be regarded as characteristic of "districts that have undergone a long continued and gentle subsidence, with few or slight upward movements, and no important faulting" (p. 16).[1] Others are Andesites, a rock-type of the "*Pacific*" suite that is held by some to be more particularly associated with regions of lateral compression (p. 298). The concurrence of the two types during the Ordovician stage of the geosyncline accords well with the other evidence we possess, of slow sinking of the region as a whole, and of compressive forces affecting certain of its parts (p. 271).

iii. Upper Valentian-Salopian.

Prof. Marr[2] in discussing the environment under which the Lower Valentian rocks of the Lake District had been formed, has shown (Fig. 113) that the British Lower Palæozoic geosyncline was at that time one gulf-like extension of a western ocean, a second extending through Germany and Sweden. He maintains that these gulfs were so land-locked that, while algæ and Graptolites throve in the surface-zone, the bottom-waters were motionless, unaerated, and lifeless. Thus he accounts for the absence of benthonic fossils, the presence of the pseudoplanktonic Graptolites, and the carbonaceous nature of the black shales which were once black muds poisoned by sulphuretted hydrogen, like those that are found in the stagnant bottom-waters of the Black Sea.[3]

In Upper Valentian times the isthmus shown in Fig. 113 over

[1] H. Dewey and J. S. Flett, *Geol. Mag.*, 1911, p. 246.

[2] J. E. Marr, *Q.J.G.S.*, vol. lxxxi, 1925, pp. 113–33.

[3] Guide to the excursion of the VII Internat. Geol. Congress, St. Petersburg, 1897, chap. xxix.

the Midlands was flooded by the sea, so that a direct communication was established between the geosyncline and the Swedish gulf.

This is evidenced by the close similarity in the life preserved as fossils in the English and Swedish Upper Valentian and Salopian. The sea over the Midlands was an epeiric one, and as it spread over the continental shelf it left its littoral facies as the so-called Llandovery Sandstone. As the water deepened, grey and purple shales, and then grey-coloured shales were deposited, but from time to time

FIG. 113.—Land and Sea in Valentian times (Stockdale Shales).
After J. E. Marr, *Q.J.G.S.*, vol. lxxxi, 1925.

and from place to place reef-limestones were formed. These are the wonderfully fossiliferous limestones of Woolhope, Wenlock, Dudley, Aymestry, Gotland, etc.

The main trough of the geosyncline was during Upper Valentian and Salopian times the scene of enormous accumulations of sediment, usually with Graptolites as the only fossils. The thinness of the Upper Valentian rocks in the Lake District is exceptional; on it there follows the greatest known thickness of Salopian strata. Stated to be 11,800 feet thick here, they resemble the Welsh or "Denbighshire" facies of the Salopian in being poorly fossiliferous shales, and silty or sandy flags, a facies remarkably different from the contemporary reef-limestones and calcareous shales of the Shropshire-Midland type. The Denbighshire facies recalls in some respects the Alpine Flysch (p. 173); and, like it, derived its material from an emerging continent.

In the Salopian, therefore, there are nowhere any of the deeper-sea sediments. The geosyncline had become so choked with detritus that although the Graptolites were there, their remains are more

sparsely preserved in the rapidly accumulated strata than in the slowly-formed black shales of the Ordovician and Lower Valentian. Eventually, deposition gained upon the depression of the crust, and signs of terrestrial conditions creep into the succeeding strata that are known as the Downtonian, the lowest part of which series consists of marine intercalations in estuarine rocks. It contains Eurypterid and fish remains of Devonian affinities. Formerly classed with the Silurian, the Downtonian is now often regarded as recording the incoming of Old Red Sandstone conditions, and therefore may be best treated as Devonian (p. 292).

Contemporary Earth-movements.—The tendency for the floor of a geosyncline to buckle in places during the cycle of sedimentation that fills it up, is recorded by the following unconformities within the Ordovician:

Girvan	Pre-Llandeilo.
Lake District . . .	Pre-Caradoc.
Church Stretton . . .	Pre-Caradoc (see p. 265).
Anglesey and N.W. Wales .	Pre-Arenig-Llandeilo.
Pembrokeshire . . .	Pre-Arenig.

In most cases these unconformities were produced by gentle flexuring, the direction of which can in rare cases be surmised. Thus in the Lake District it seems to have been N.N.E. In some cases the movements added to the land masses, and in other cases produced islands.

At the beginning of Silurian times more extensive movements seem to have set in, especially in South Wales, and along the Welsh Marches which lay at or near the north-western margin of the Midland massif.[1] So extensive were these movements in Shropshire that Upper Valentian rests in turn upon all the subdivisions of the Ordovician, and even on Pre-Cambrian rocks in the Shelve-Longmynd district. This involves the destruction of some thousands of feet of strata in the period between the Caradocian and the Upper Valentian (Llandovery Sandstone). A considerable land area is thus indicated. At Rhyader there is proof of great erosion between the Lower and Upper Valentian; at Builth the Upper Valentian lies on sharply folded Llandeilian strata; two breaks occur in the Valentian of Llandovery; in South Pembrokeshire Ludlow rocks lie directly on the Llanvirnian.

All these movements may be regarded as premonitory symptoms of the great Cāledonian Orogeny to which our attention may now be turned.

[1] W. B. R. King, *op. cit.*, 1928, p. 695.

CHAPTER XXII

THE CALEDONIDES: A STUDY OF A DEEPLY DISSECTED MOUNTAIN-RANGE

It has been made clear in the last chapter that the ideal development of a typical geosyncline involves anticlinal movements on its floor, and that its completion culminates in the uprise of mountain-chains on its site. Evidence of contemporary movements during the

FIG. 114.—The Caledonian mountains of Britain and Scandinavia.

1. Horizontal ruling, forelands; 2. Full black, Belt II; 3. Stippled, Belt III, of Caledonian Orogeny; T. Trondhjem. Caledonian trend-lines shown in Britain.

growth of the Lower Palæozoic Geosyncline has just been given. It remains now to examine the mountain-system that arose from the buckling of the geosynclinal sediments. The chains (Figs. 111, 114) are known as the *Caledonides* on account of their great

development in Scotland, to which country they even now impart [1] a north-east to south-west grain, which corresponds with the general trend-direction of the folding in Britain and Ireland. There are, however, places where the strike of the folds is different. Thus in the North-West Highlands and in Central Wales it is north-north-east to south-south-west; in South-West Wales and South Ireland it is almost east and west.[2] This is suggestive of an arc-like arrangement of the chains, which has been shown to be a characteristic of recent folded mountains (p. 178).

There is no doubt that the Caledonides were originally continued across the North Sea into Scandinavia, the western mountain ranges of which are their worn-down stumps. The general north-easterly trend must therefore have been maintained from Scotland to Southern Norway, and is continued there; though more in the north of the peninsula it becomes north-north-easterly. The probable continuation of the chain into Spitzbergen and Northern Greenland is shown on Fig. 111, which also indicates the trend of the roughly contemporary Acadian chain in Eastern North America.

The time during which movement took place was a protracted one. In Southern Scotland the maximum disturbance appears to have been a feature of the time immediately preceding the Dittonian [3] or upper subdivision of the Lower Old Red Sandstone (Lower Devonian), for we find that all the rocks up to and including the Downtonian or lower subdivision of the same formation, had been involved in the folding,[4] and had been deeply eroded before being covered by the Dittonian. Elsewhere the main movements cannot be dated so accurately.[5] It is probable that in the Scottish Highlands the principal folding had occurred before this time. Coming southwards, however, to Shropshire and South Wales we note that sedimentation went on continuously from the Silurian to the

[1] By virtue of their "resurrection rather than their survival" as mountains (E. B. Bailey).

[2] This direction may have been superimposed by the Altaid Armorican movements (p. 75).

[3] The classification of the Continental Devonian deposits here adopted is given on p. 292, together with the reasons for placing the Downtonian in the Devonian. This latter alteration makes it necessary for readers to note that "post-Silurian" in the literature implies post-Downtonian, whereas here it denotes post-Ludlovian.

[4] Except in Lanark and Forfar.

[5] In Forfar the Dittonian and Downtonian are conformable, but the latter lies unconformably on the schists of the Dalradian Series (p. 249), so that it is clear that in the Scottish Highlands the principal folding had occurred before this time. The thrusting of the Cambro-Ordovician Durness Limestone in the North-West Highlands and the folding of Cambrian and Ordovician rocks along the Highland Border demonstrates only a lower time-limit to the disturbances.

end of Lower Old Red Sandstone times, being terminated then by comparatively gentle flexuring.

In Scandinavia the Valentian is the highest Silurian formation definitely known to be involved in the disturbances.

Movement was renewed at later stages in the north of Britain, but on a reduced scale of violence. The evidence for this is the unconformity that is found everywhere below the upper Old Red Sandstone.

Finally there was another recrudescence of elevation in Shropshire and the Welsh borderland at the end of Devonian times, which was instrumental in producing the ridge of land which separated the South-West from the North-West Provinces of the Lower Carboniferous seas (p. 310).

It is not, however, the purpose of this chapter to discuss the age and palæogeographical effects of these movements, but to study them more particularly with a view to seeing what light the resultant structures throw on the methods of mountain-building. The vast denudation that has taken place in Britain since the elevation of the Caledonides enables us to see deep-seated structures that are perhaps barely visible at the erosion-level so far reached in the Alps (Chapter XVI). Since the Scandinavian part of the chain has been denuded to a still lower level than the British, some observations on its structure will be included.

The reader will realize that with the rather fragmentary nature of the evidence which in itself is difficult to interpret, a certain amount of speculation can easily creep into the theories devised to explain the data. The explanations here set out attempt to be an exposition of current views, certain of which are perhaps hardly free from this speculative element.

The British Caledonides, like the Lower Palæozoic Geosyncline, trended north-eastwards, roughly parallel to the ancient land-mass (Atlantis) that lay towards the north-west (Fig. 111). The region of greatest disturbance and probably of the highest ranges, lay over the central Highlands, the present Midland Valley, and the Southern Uplands of Scotland. Yet almost equally disturbed are the Lower Palæozoic rocks of the Lake District, Isle of Man, Anglesey and North Wales. To the east of the Principality gentle folding seems to be the rule, but owing to the cover of newer rocks in the Midlands and southern counties we know but little of the Caledonian basis on which they rest.

In the geosynclinal concept outlined in the last chapter the stable crust-blocks bordering the geosyncline become the foreland and backland, or, on Kober's hypothesis, the two forelands, of the orogen that arises on its site. If we search for the forelands of the Cale-

donides we find that in the North-West Highlands of Scotland there is an undisturbed zone in the Hebrides and along the north-west coast, towards which the highly disturbed rocks that were involved in the mountain-building have been thrust. This strip of undisturbed country is the sole relic in Britain of the once-great northern continent of Atlantis whose influence on British geology can be seen throughout Palæozoic and Mesozoic times. With respect to the British Caledonides it acted as the north-western stable-block or foreland (Fig. 116, autochthonous foreland).

The corresponding structure on the other or south-east side of the range is not so easily identified in Britain; though the relatively small disturbance of the Lower Palæozoic rocks in the Midlands suggests that they may have formed part of it. Bailey states that here the edge of the chain was "a mere matter of foothills grading into foreland."

In Scandinavia, however, the mountain-system ends off towards the east or south-east down the middle of the peninsula, the highly disturbed rocks of the mountain zone being apparently thrust south-eastwards on to the stable-block of the so-called "Baltic Shield" which is composed of Pre-Cambrian rocks, veneered in places by undisturbed Lower Palæozoic sediments.

Atlantis, and the Baltic Shield with the Russian Platform to which it belongs, appear therefore to have acted in the capacity of forelands, one on either side of the orogen (Fig. 114), much in the manner postulated by Kober (p. 179, Fig. 77), in that the downward and inward thrust of the two, produced at the surface an apparent upward and outward thrust of the crushed rocks.[1] Whether this view be the true explanation or not, there is remarkable similarity, though in opposite directions, between the Scandinavian and British portions of the chain (Fig. 114).

In each region, as pointed out by Frodin,[2] we may recognize:

i. An autochthonous belt, little affected by the movements and belonging to the foreland.

ii. A belt of thrusting and low dips, with inversions and other signs of strong tangential compression and mass-disturbance.

iii. A central folded belt exhibiting high dips and a varying, but often intense, metamorphism. This belt may contain large-scale igneous manifestations. The folding may

[1] L. Kober, *Bau d. Erde*, Berlin, 1921. This conception was independently suggested in the case of the Scandinavian Caledonides by B. Smith, *Q.J.G.S.*, vol. lxxvi, 1920, p. 402. See also L. J. Wills and B. Smith, *Q.J.G.S.*, vol. lxxviii, 1922, p. 221.

[2] G. Frodin, *Bull. Geol. Inst. Upsala*, vol. xviii, 1922, pp. 57–197, and *ibid.*, p. 199.

display a fan-structure, with considerable minor displacements by recumbent folds and thrusts; but the mass disturbances are generally on a lesser scale than in Belt II.[1]

The British Caledonides

Belts I and II.—The structure of Belts I and II in Britain has been worked out in great detail in the North-West Highlands of Scotland by C. Lapworth, Peach and Horne, and other members

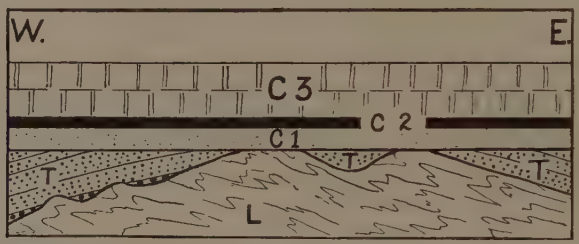


Fig. 115.—Diagram to show the folding and denudation of the Torridonian in Pre-Cambrian times, and the difference between the sub-Cambrian and sub-Torridonian unconformities. Based on Peach and Horne.

C 1–3, Cambrian; 1, Basal Quartzite; 2, Fucoid Beds; 3, Durness Limestone; T, Torridonian Sandstones; L, Lewisian Gneisses.

of the Geological Survey. Four distinct rock-groups are met with in the following order from west to east: Lewisian gneiss; Torridonian sandstone; Cambrian quartzite, shales and limestones; Moinian schists. This order is also that of their superposition on one another, the Lewisian gneisses and schists forming a substratum of metamorphic rocks that had been involved in great earth-movements in Pre-Torridonian times. As already described in Chapter XX (p. 254) the Lewisian had been deeply eroded before the Torridon Sandstone Series was deposited. The latter, as a rule quite unmetamorphosed, lies in its principal outcrops almost horizontally. Nevertheless it can be shown to have been thrown into gentle flexures, and to have been subjected to so much erosion in Pre-Cambrian times, that in places it was completely removed; for the Cambrian base rests sometimes on Torridonian and sometimes on Lewisian (see Figs. 115, 116). This will be seen later to be of some importance in interpreting the tectonics.

Unlike the sub-Torridonian surface, that found below the Cambrian is quite even, and for this reason is generally regarded as a plane

[1] This statement may need revising if the nappe structures claimed by some workers to occur in the Highlands, are proved to exist and to have originated in the Caledonian orogeny (see p. 280).

of marine denudation. The strata are usually quite unmetamorphosed, and in Belt I, dip as a rule consistently to east-south-east.

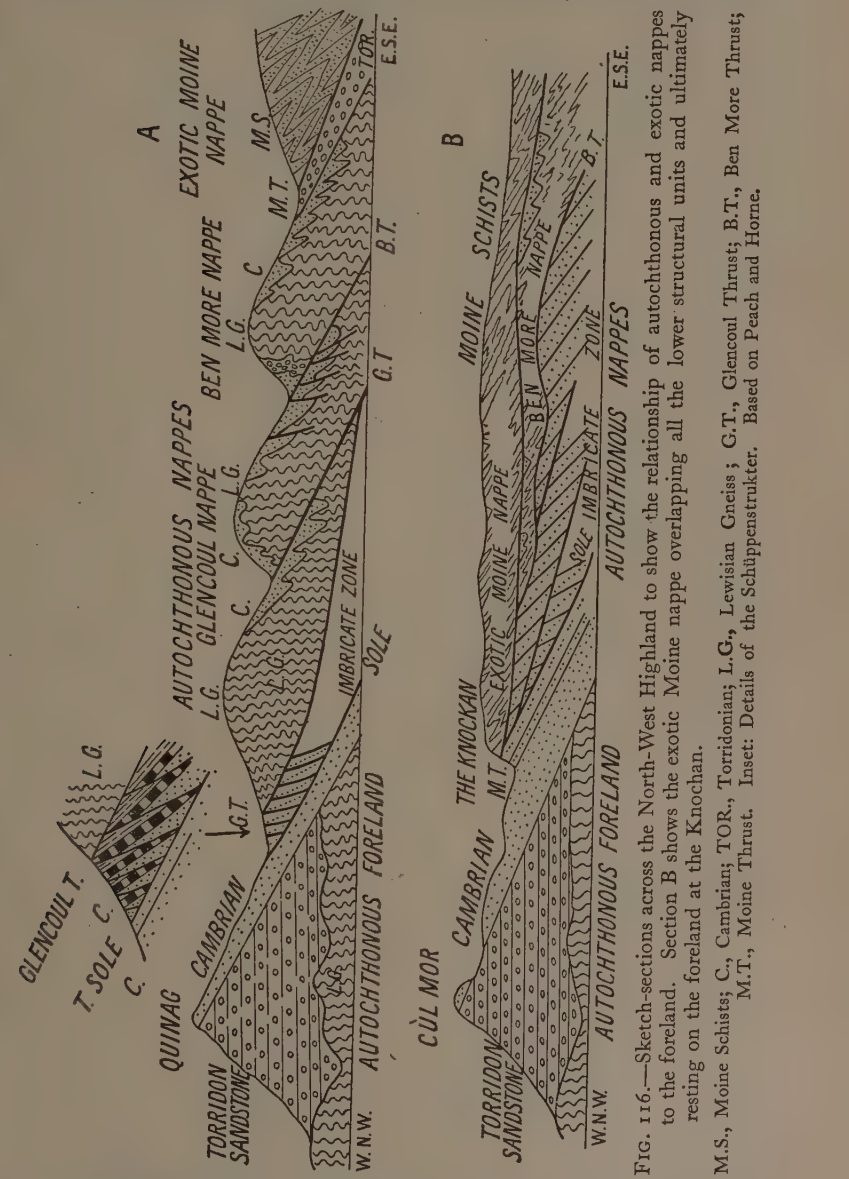


FIG. 116.—Sketch-sections across the North-West Highland to show the relationship of autochthonous and exotic nappes to the foreland. Section B shows the exotic Moine nappe overlapping all the lower structural units and ultimately resting on the foreland at the Knochan.

M.S., Moine Schists; C., Cambrian; TOR., Torridonian; L.G., Lewisian Gneiss; G.T., Glencoul Thrust; B.T., Ben More Thrust; M.T., Moine Thrust. Inset: Details of the Schüppenstrukter. Based on Peach and Horne.

The Cambrian sequence displays a constant and very distinctive lithology as follows:

3. Durness Limestone—dolomites and limestones.
2. Olenellus Beds—dolomitic shales with quartzite bands.
1. Basal quartzite—buff or pinkish quartzite.

The distinctive nature of these subdivisions has been a useful guide in elucidating the structures.

The Moine Schists are mostly micaceous quartzose schists, which probably represent highly metamorphosed clastic sediments. They only occur in Belt II.

The general structure of Belts I and II may now be discussed. The Lewisian, Torridonian and Cambrian systems, where undisturbed, constitute the foreland (Belt I), towards which small and large thrust-sheets or nappes (Belt II) were driven from east or south-east (Figs. 116 A and B). As in the Alps, the nappes are piled up one on another. The lower ones are relatively small; but the size and the distance they have travelled increases in an upward sequence. Since the nappes and their underlying thrust-planes show in general a gentle inclination to the east-south-east, one encounters in that direction successively higher nappes, until eventually the huge Moine Thrust is met with. Up to this point the nappes are *autochthonous*, in that they consist of the same rocks as the foreland (Lewisian, Torridonian and Cambrian). The Moine Thrust on the other hand introduces a vast nappe that must be regarded as *exotic*; for it is composed of the Moine Schists which cannot be matched in the foreland. Their outcrop stretches away for miles to the east and south, and in fact make up most of Scotland north of the Great Glen.

Looked at in still greater detail Belt II commences on the side nearest to the foreland with a strip of country of varying but often considerable width, in which small slices of Cambrian are piled on one another like the slates on a roof. This is effected by countless thrust-planes, whose dip is slightly steeper than that of the beds, which are rarely if ever inverted. This belt is the region of Schuppenstruktur or imbricate structure. In it the thrust-planes affect only the higher rocks of the foreland, and are individually of minor importance; but the piling up of the slices implies the existence of major thrust-planes above and below, the latter of which is known as the "sole" (see Fig. 116 A).

The area of imbricate structure is in turn overridden by a series of large nappes (Figs. 116, 117). Of these we may mention the lowest in the well-known Assynt district, the Glencoul Nappe, which is composed of Lewisian gneiss and its overlying burden of Cambrian. The absence of the Torridonian shows that the nappe was derived from the foreland nearby (cf. Fig. 115); for here the Cambrian rests directly on the Lewisian. But when the next important and

much larger Ben More Nappe is examined, its Lewisian core is found to carry Torridonian sandstone as well as Cambrian. The material of the nappe was therefore derived from a district where Torridonian sandstone intervened between Cambrian and Lewisian, that is to

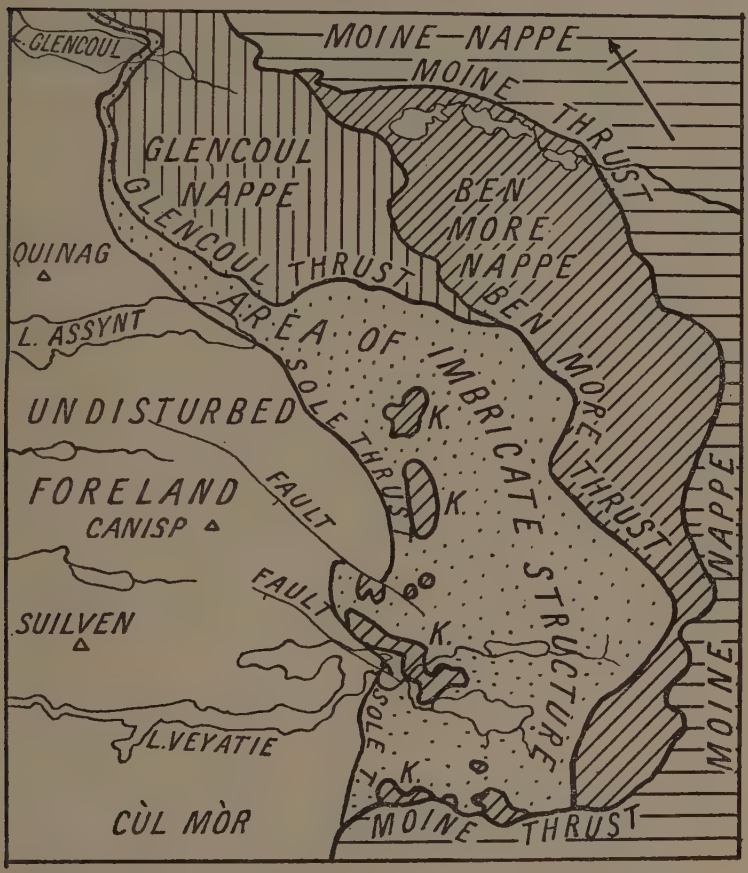


FIG. 117.—Sketch Map of Nappes in N.W. Highlands.
K = Klippe of Ben More Nappe. Based on Peach and Horne.

say, from east of the Pre-Cambrian flexure referred to on p. 276, as accounting for the local erosion of the Torridonian (Fig. 115).

In the large nappes, of which the Glencoul and Ben More[1] can alone be cited here, it is not uncommon to find inversions of the

[1] In the map, Fig. 117, the area shown for the Ben More Nappe includes the outcrop of the Sgonnan Beag Nappe.

rocks especially in proximity to the thrust-planes. It seems probable that this is better regarded as due to the frictional drag along the thrust than as a sign that the nappe originated as an overfold which was later broken by thrusting.

Finally as stated above, the Moine Thrust introduces a series of rocks that are apparently complete strangers to the foreland, and are therefore held to be derived from an unknown distance to the south-east. The map (Fig. 117), by indicating the several major tectonic units, helps us to see the overlap of the higher nappes across the lower, culminating in the Moine Nappe which, lying nearly horizontally, transgresses all the lower ones and finally comes to lie upon the undisturbed succession of the foreland, as may be seen at the famous cliff known as the Knockan (Fig. 116 B). Here the highly metamorphic but apparently well-bedded Moine Schists overlie unaltered Durness Limestone; an anomalous arrangement which was only made intelligible when the possibility of large-scale lateral thrusting had been recognized. The section is particularly deceptive on account of the apparent conformity of the schists and limestones. But the appearance is entirely due to the development of planes of parting that resemble bedding-planes, but which in reality are produced in the formation of the *mylonites* [1] or "milled rocks" that have resulted from the crushing, shearing and dragging of both schists and limestone in the neighbourhood of the giant thrust-plane.

Belt III.—The central folding belt (III) of the British Caledonides extends from the south-eastern limits of the Moine Schist country just described, across the Central Highlands, southwards as far as the Lake District and North Wales (Fig. 114, 3).

Scotland.

The Central Highlands are formed by a metamorphic series known as the Dalradian, about the age and structure of which great divergence of opinion prevails. Thus some hold the rocks, the metamorphism, and the folding to be mainly Pre-Cambrian in age; others would regard the rocks as partly Pre-Cambrian but mainly Palæozoic, and the structures and some of the metamorphism to be due to the Caledonian orogeny.[2] Further, it has been usual in the past to consider these rocks as arranged in complex fan-folds, but recently the presence of large recumbent folds and nappes, analogous to those of the Alps, has been claimed. In the present state of our knowledge therefore it is unsafe to draw upon this region for precise information

[1] C. Lapworth, *Intermediate Textbook of Geology*, 1910, p. 144.

[2] In any case the structures as we see them must have been in part produced by the Caledonian earth-stresses.

on the tectonics of the Caledonides, but the student wishing to appreciate the difficulties is referred to the literature listed in the note.[1]

The connecting link between the Highlands and the Southern Uplands lies buried beneath newer strata in the Midland Valley of Scotland, the whole having been faulted down by great north-east to south-west dislocations (the Highland and Southern Uplands Faults, Fig. 128). Only in the Pentlands do we see a glimpse of the buried mountain chain (Fig. 127).

The structure of the Southern Uplands was first unravelled by Charles Lapworth who was able to show that the persistent dips were misleading, being in reality due to intense folding, the arrangement of which he demonstrated by means of the graptolite zones that

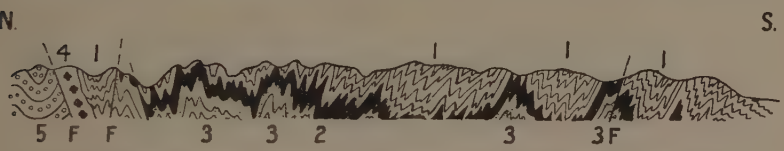


FIG. 118.—Sketch-section across the Southern Uplands through Sanquhar and Kirkudbright; based on Peach and Horne.

1, Valentian; 2, Arenig-Llandeilo-Caradoc; 3, Arenig Volcanic rocks; 4, "Newer" Granite; 5, Old Red Sandstone; F, Faults.

he had been able to establish.[2] The Geological Survey has since then mapped the district in great detail and confirmed Lapworth's results.[3]

Broadly speaking the Lower Palæozoic strata are here elevated into a complex *fan-anticline* or *anticlinorium* (Fig. 118), the axis of which lies not far south-east of the bounding fault referred to above. The minor folds on the flanks of the anticlinorium are usually packed tightly together so that their limbs are parallel to one another and to their axial planes, an arrangement known as *isoclinal folding* (Fig. 119). The intensity of the folding is best appreciated when it is realized that across the centre of the region 4,300 feet of Ordovician and Valentian strata, usually displaying high dips, covers by reduplication a belt of country 25 miles wide. In many cases the folding is complicated by thrust-faulting which cuts out one limb

[1] J. W. Gregory in *Handb. d. regionalen Geol.* E. B. Bailey, various papers in *Q.J.G.S.* from 1910. G. L. Elles, *Q.J.G.S.*, 1926, vol. lxxxii, p. 304. G. Barrow, *Q.J.G.S.*, 1893, vol. xlix, p. 330, *Proc. Geol. Assoc.*, xxiii, 1912, p. 274. Various memoirs of Geol. Surv. of Scotland. C. E. Tilley, *Q.J.G.S.*, 1925, vol. lxxxi, pp. 100–109.

[2] C. Lapworth, *Q.J.G.S.*, vol. xxxiv, 1878, p. 240, and vol. xxxviii, 1882, p. 537. *Geol. Mag.*, 1889, pp. 20 and 69.

[3] B. N. Peach and J. Horne, "Silurian Rocks of Britain, vol. i, Scotland," *Mem. Geol. Survey*, 1899.

of a fold. This may be repeated so often as to produce a sort of small-scale imbricated structure (Fig. 119).

The direction of dip of the isoclinal folds is inward towards the main anticlinorial axis on its two flanks (Fig. 118). This is the normal arrangement in a fan-anticlinorium (Fig. 120), whereas apparent outward dips characterize a fan-synclinorium.

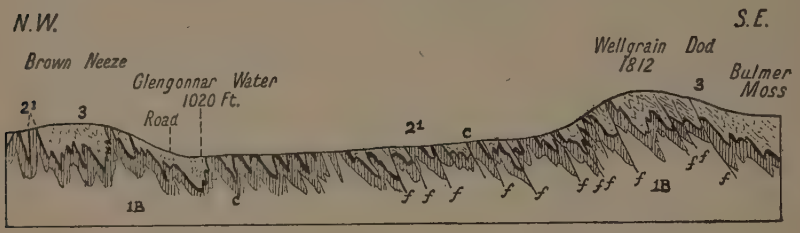


FIG. 119.—Isoclinal Folding and Minor Thrusting in S. Uplands. After Peach and Horne.

1B, Arenig volcanic rocks; C, Radiolarian chert; 2¹, Glenkiln Shales; 3, Caradoc; *f*, fault. Length of section = 1¼ miles. From *Mem. Geol. Survey*, "Silurian Rocks of Britain, vol. i, Scotland," 1892. By permission of the Controller of H.M. Stationery Office.

The rocks of the Southern Uplands have not undergone the high degree of metamorphism that is found in the Highlands and in many parts of Scandinavia (p. 288). The principal change, apart from compacting and hardening, is best seen in the finer-grained rocks, which have in some places acquired a *slaty cleavage*. This term refers to the development of new closely-spaced divisional or cleavage-planes,

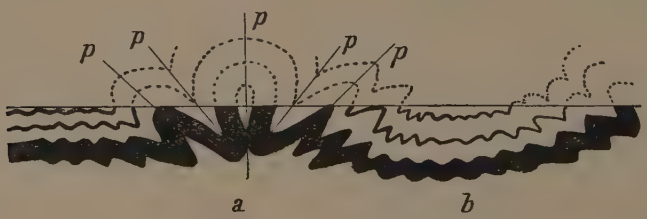


FIG. 120.—Diagram across "Fan-folded" Strata.

a, Fan-structure, double-fold, or anticlinorium; *b*, synclinorium; *pp*, axial planes.

along which the rock now splits more readily than along the bedding. Roofing slates have this property developed to a high degree.

Slaty cleavage is of two types, the more usual being *flow-cleavage*, the development of which is brought about by the mechanical re-orientation of the mineral particles so that their longer axes come to lie at right angles to the direction of pressure. For this reason it is only imperfectly displayed in sediments composed of more or less

spherical particles, but is common in rocks formed of, or capable of developing, needle-shaped or platy minerals. The re-orientation is frequently accompanied by a certain amount of re-crystallization.

The second type of cleavage is known as *strain-slip cleavage*. It occurs in rocks that have yielded to the pressure by adjustments along minute thrust-faults, which appear as closely-spaced shear-planes. The imbricate structure of the North-West Highland thrusts is here repeated on a microscopic scale. This type of slate grades into a schist.

In the Southern Uplands cleavage and schistosity is limited to certain belts "where probably the mechanical strain producing intersticial movements has been most intense."

The Caledonian movements in Scotland were accompanied in their later stages by the intrusion of large granite masses. These so-called "newer-granites" are commonest in the Highlands, but three big ones occur in the Southern Uplands (see p. 298 and Fig. 128).

The Lake District.

In the Lake District the Lower Palæozoic comprises:

Silurian,	Kirkby Moor Flags . .	Ludlow.
	Bannisdale Slates . . .	,,
	Coniston Grits . . .	,,
	Upper Coniston Flags . .	,,
	Lower Coniston Flags . .	Wenlock.
	Stockdale Shales . . .	Valentian.
Ordovician,	Coniston Limestone . .	Bala.
	Borrowdale Volcanic Series .	Llandeilo.
	Skiddaw Slates . . .	Arenig and Cambrian.

Viewed broadly, the rocks appear to have been uplifted into an anticline along an east-north-east axis passing through Skiddaw, where the oldest formation, the Skiddaw Slates crop out. But the relationship of the different formations one to another is not by any means simple. This is particularly so in regard to the nature of the lower and upper boundary of the Borrowdale Volcanic Series. There are many signs of intense lateral compression; for example, strike-faulting, isoclinal folding, slaty cleavage. All these and other factors introduce elements of difficulty and uncertainty into the interpretation of the data. Under these circumstances it is not surprising that more than one explanation has been put forward.

The older theory was advanced by Prof. J. E. Marr in collaboration with Dr. A. Harker. They urged that the bounding surfaces of the Borrowdale Volcanic Series are in most places fault-planes making a

relative low angle with the horizon.[1] On their view the limits of the formations are essentially strike-faults, which separate slices of rock that have been driven northwards at different rates by the earth-stresses.

Since it is believed that the apparent order of superposition is the true sequence, Prof. Marr inclines to the view that the dislocations at the base and top of the Borrowdale Series are *lag-faults*, by which term it is implied that the lower and older rocks have advanced farther to the north than the higher and younger: the Borrowdales have lagged behind the Skiddaw Slates, and the Coniston Limestone Series behind the Borrowdales. These relations require the existence at a lower level of a thrust-plane on which the whole has moved (Fig. 122, T).

On their hypothesis not only did the slices move differentially,

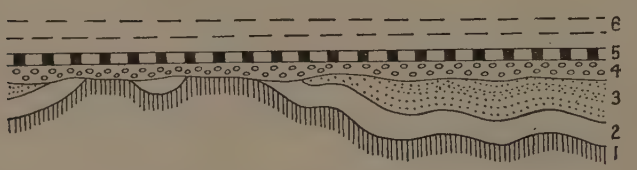


FIG. 121.—The unconformity between the Coniston Limestone (5) with basal beds (4), and the older Ordovician rocks (1–3).

1, Skiddaw Sandstone; 2, Skiddaw Slates; 3, Borrowdale Volcanic Series; 6, Silurian. Based on J. F. N. Green.

but parts of individual slices were thrust forward to different degrees. The fractures that separate the several portions are roughly parallel to the dip, and exhibit evidence of horizontal movement. They are known as *tear-faults*. Both lag- and tear-faults are usually marked by brecciation of the rocks affected.

Though Marr and Harker's interpretation held the field for a long time, it has recently been challenged by Mr. J. F. N. Green [2] whose reading of the evidence is very different; and appears to offer a simpler and more convincing explanation of the tectonics.

He claims in the first place that there is no break between the Borrowdale Series and the Skiddaw Slates, but that an important unconformity occurs below the Coniston Limestone Series.[3] This was brought about by post-Llandeilo and pre-Bala folding that threw

[1] J. E. Marr, *Proc. Geol. Assoc.*, vol. xvi, p. 449, and *Geol. of Lake District*, espec. pp. 75–82.

[2] J. F. N. Green, "Structure of the Lake District," *Proc. Geol. Assoc.*, vol. xxxi, 1920, p. 109.

[3] See also B. Smith, *Geol. Mag.*, 1924, p. 163.

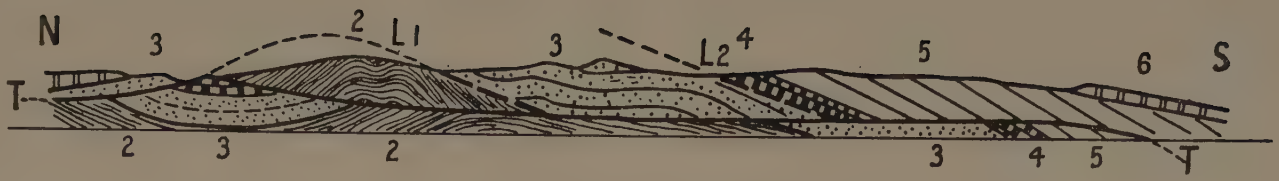


FIG. 122.

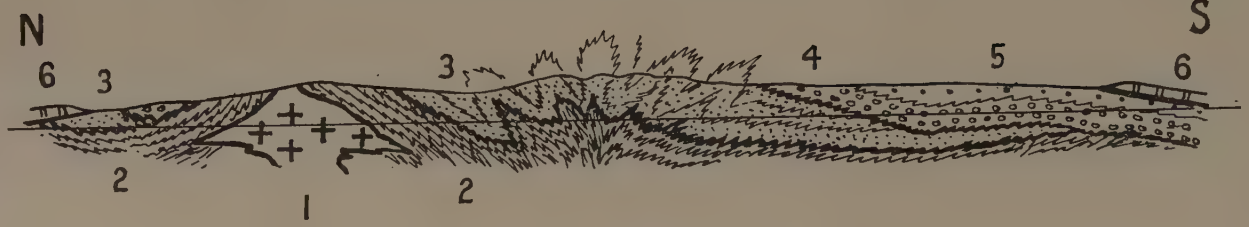


FIG. 123.

Diagram-sections across the Lake District; 122, based on J. E. Marr; 123, on J. F. N. Green.

T, thrust; L1, L2, lag faults. 1, Skiddaw granite; 2, Skiddaw slates; 3, Borrowdale volcanic series; 4, Coniston Limestone; 5, Silurian; 6, Carboniferous Limestone and volcanics.

the Skiddaw Slates and Borrowdale Volcanic Series into gentle north-east to south-west undulations. Of these the most important was a major anticline in the Skiddaw region, which was planed down before the Coniston Limestone Series was deposited. The relations at the end of Silurian times are illustrated in Fig. 121.

In Devonian times the rocks were involved in the Caledonian orogenic movements (Fig. 123). They were folded into a huge complex anticlinorium whose axis passes east-north-eastwards across the main outcrop of the Borrowdale Volcanic Series. To the north a synclinorium was initiated north of Skiddaw; while to the south another downfold of simpler nature accounts for the main outcrop of the Coniston Limestone Series and of the Silurian. In Green's opinion the junctions of the principal subdivisions, as usually mapped, are in reality the junctions of sheets of rock that are themselves highly contorted and puckered within the limits of the sheets. For this reason while the observed dips of the strata are frequently very high (being of the nature of isoclinal dips) the disposition of the sheets (sheet-dip) is relatively horizontal. He avers that Marr and Harker have misinterpreted the junctions of the sheets as lag-faults, and by not appreciating the magnitude of the pre-Bala erosion have been forced, in order to explain the observed distribution and arrangements of the rocks, to postulate huge movements along these imaginary dislocations.

Wales.

Over a great part of Northern and Central Wales the structure is not unlike that of the Lake District and Southern Uplands; and consists of sharp isoclinal minor folds superimposed on rolling major undulations. This is clearly brought out in Fig. 124. But where the hard masses of Ordovician volcanic rocks occur they have formed, as it were, local obstacles to the free movement of the strata, and have thus exercised a differential effect which is expressed by thrusting, both on a large and a small scale. The largest known Welsh example is the Carmel Head Thrust, found in Anglesey.[1] It carries forward from the north on to the Ordovician a nappe of Pre-Cambrian rocks (Mona Complex) 30 square miles in visible extent The amount of movement on a conservative estimate is 20 miles, but Greenly suggests it may well be 40 or more.

In Wales also the compressive stresses have set up a slaty cleavage in those rocks that were susceptible to it, and as a result we have the famous roofing slates of Penrhyn (Llanberis), Dinorwic, Nantlle, and Ffestiniog.

Great master-faults enter largely into the tectonics of North Wales,

[1] E. Greenly, "Geol. of Anglesey," vol. ii, p. 541, *Mem. Geol. Surv.*, 1919.

but their relation to the whole structure, and that structure itself are not thoroughly understood.

Enough has now been said to show that in Belt III from the Southern Uplands to Central Wales the sediments of the Lower Palæozoic Geosyncline have been crushed by lateral pressure into major and minor folds, many of which have been broken and displaced by thrust-faulting.

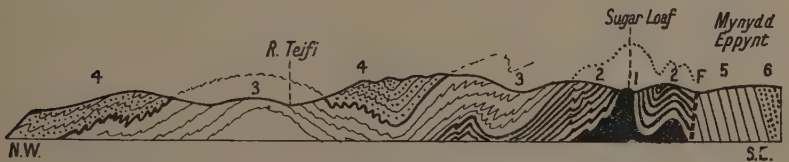


FIG. 124.—Sketch-section across Central Wales.

1, Dicranograptus shales; 2, Upper Bala; 3, Lower Valentian; 4, Upper Valentian; 5, Wenlock-Ludlow; 6, Old Red Sandstone. Length of section, 30 miles. Based on O. T. Jones.

THE SCANDINAVIAN CALEDONIDES

The mountain-belt extending through Norway from the south-west coast near Stavanger to the Arctic Ocean in Finnmarken, together with an adjoining strip of West-Central Sweden is formed of the deeply denuded remnants of the Scandinavian Caledonides. Their structure offers many analogies with that of the British part of the chain, once it is recognized that the apparent direction of superficial movement here was towards a foreland lying to the south-east instead of to the north-west (p. 275). As in Britain so here, there has been and still is a considerable divergence of opinion regarding the "mountain problem" (Figs. 114, 125).

Frodin's classification of the region into three belts has been given on p. 275.

Autochthonous Belt I or Foreland.—The comparison of the Scotch and Swedish autochthonous foreland is very close.

Systems comprising the Foreland.

Scotland.	Scandinavia.
Cambrian and Ordovician (part)	Eo-Cambrian [1] to Silurian
Torridonian sandstones	Jotnian sandstones
Pre-Torridonian (Lewisian gneiss, etc.).	Pre-Jotnian (late Pre-Cambrian granites, porphyries, etc.).

The basal complex of Pre-Jotnian rocks is probably of later date

[1] Brögger's name for the Sparagmite Formation of Central Norway, which is an arkose formation of greater age than the *Olenellus* zone of the Cambrian, but is not separated from that zone by any unconformity.

than the Lewisian, but the Torridonian and Jotnian resemble one another closely in their unconformable bases and in being predominantly red sandstones or arkoses. The Lower Palæozoic rocks present in Scandinavia embrace a larger range of formations (Eo-Cambrian to Valentian) than are found in the North-west Highlands. This "Eastern Facies" of the Jotnian and Lower Palæozoics exhibit no metamorphism in the foreland, as, it will be remembered, is the case with the Torridonian and Cambrian in Scotland.

Belt II.—The rocks of the foreland lie to the south-east of the mountain-belt, and appear as inliers in large "windows" cut by erosion in the over-thrust masses composing Belt II, which consists of the Koli, Åre and Seve schists. Törnebohm has maintained that the Åre and Seve schists which closely resemble the Moinian of Scotland, have been thrust over the edge of the foreland as a huge nappe with a displacement in some cases of as much as 80 miles.[1] The Koli Schists of the Tännforsfeld (Fig. 125) display the "Western Facies" (see below), and are also held to have been carried there by thrusting. On this view all these schists are quite exotic where they rest on the foreland, although generally recognized as metamorphosed Lower Palæozoic and Sparagmite formations. Frodin has, however, tried to demonstrate that they are more or less autochthonous, and that their occurrence can well be explained by double-folding or fan-folding of the Lower Palæozoics in the synclinal belts of the mountain-system. According to him these schists can be seen in the anticlinal belts to be involved in the same fan-folding, and he claims that the anticlinals are on either side overthrust by rock squeezed out of the synclinals (Fig. 125). Frodin's views are open to suspicion in view of the general discredit in which "double-folding" is held as an explanation of recumbent folding and horizontal displacements in present-day theories of mountain-building (see Chapter XVI).[2]

Belt III, best known in the Trondhjem district, is one of high dips. Generally speaking, it exhibits a very advanced grade of metamorphism; but there are parts of it that have been less affected, in which Lower Palæozoic fossils have been found. The rocks are generally accepted as being metamorphosed Lower Palæozoics of a "Western Facies," known as the Koli schists (Fig. 125). In some parts of Belt III there are large igneous intrusions, formerly regarded as Pre-Cambrian, that in many cases have now been proved to date from the time of the earth-movements. This third belt is

[1] A. E. Törnebohm, *Svenska. Vetensk. Akad. Handl.*, Bd. xxviii, 1896.

[2] In addition to literature already cited, see O. Holtedahl, "The Scandinavian Mountain Problem," *Q.J.G.S.*, vol. lxxvi, 1920, pp. 387–403. With many references.

of particular interest because it represents a central part of the mountain-system where the down-folded sedimentary rocks that once covered the Pre-Cambrian, have been most deeply depressed and most highly compressed between the more rigid blocks on either side. A general fan-folding has been detected, but the folds in this case have nearly vertical axial planes in contrast to the more recumbent positions that characterize those of Belt II. Mass-displacements by thrusting are fairly insignificant in the centre, but increase in importance towards the margins of the downfold (Figs. 125,

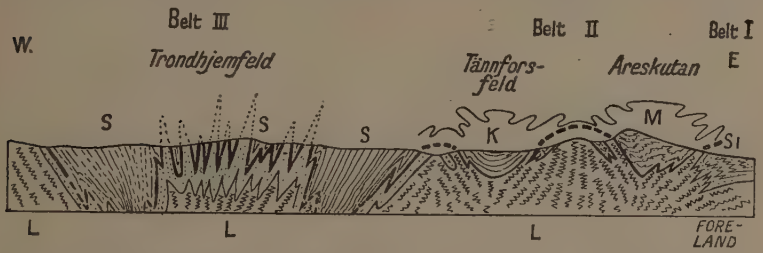


FIG. 125.—Diagrammatic section across the Scandinavian Caledonian chain. Heavy broken line above the profile, Törnebohm's thrust-plane explanation; thin continuous line, Frodin's fan-folding explanation, of the Koli and Åre schists. The profile itself adapted from Frodin.

L, Pre-Cambrian foundation; S, Lower Palæozoics, Western facies, usually highly metamorphosed; S1, Lower Palæozoics and Sparagmite, Eastern facies; K, Koli Schists (? metamorphosed Lower Palæozoic); M, Seve Schists, including Åre schists (? metamorphosed Lower Palæozoic and Sparagmite).

126). It has been argued by Frodin that the fan-structures of Belt III in Britain (Central Highlands and Southern Uplands), associated, as they are, with a low grade of metamorphism and with relatively insignificant plutonic igneous manifestations, represent the type of structure to be expected at a fairly high level in the fold-system (Fig. 126 A), and that below them a structure may exist which would be comparable with that of the Trondhjem district where erosion has reached to greater depths (Fig. 126 B).

In concluding this brief survey of the method of mountain-building exhibited by the Caledonian Chains in Britain and Scandinavia, it must be pointed out that where, as for example in the North-West Highlands and Anglesey, a nappe-structure can be best demonstrated, it differs from that of the Alps in that the rocks have yielded by fracture rather than by flow, so that recumbent folds are rare. In other cases where that structure has been invoked to explain the arrangement of the rocks, it has as a rule been contraverted; but this does not necessarily imply that it is the wrong explanation. Yet in many parts of the chain the theory of complex fan-folding appears to be

competent to explain the disposition of the rocks. This is especially true of the Southern Uplands.

It is quite clear that, even if the ancient mountains have not fully yielded up their secrets, they display abundant evidence of the crumpling and packing of the geosynclinal rocks of which they are composed, with a resultant narrowing of the belt of crust originally covered by them, on a scale comparable with that estimated in the case of the Alps (p. 185).

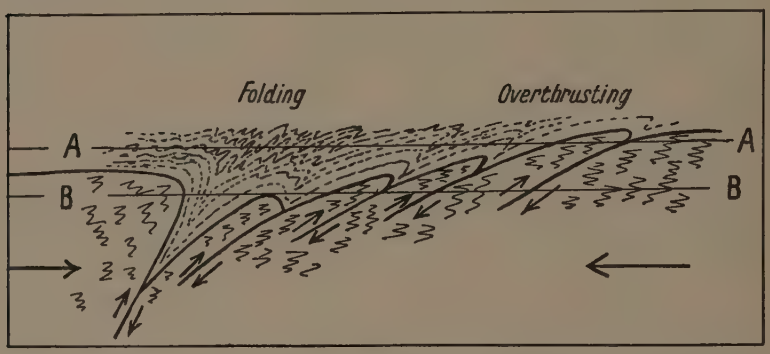


FIG. 126.—Diagram of an Asymmetrical Tectonic Basin with an infolded sedimentary cover.

A, Erosion-level in British Caledonides; B, Erosion-level in Scandinavian Caledonides. Based on Holmquist.

Finally, if we refer again to Kober's conception of an ideal orogen, as illustrated by Fig. 77, it seems possible to recognize in Belt II, with its giant mass-displacements, the bordering chains (Randketter), directed north-westwards in Scotland and south-eastwards in Scandinavia; while the isoclinal fan-folding of Belt III in the two countries may perhaps represent the structure of that part of the orogen to which he gives the name Betwixt-mountains (Zwischengebirge) (p. 179)

VIII. EPEIRIC ENVIRONMENTS, MAINLY IN LAKES, ESTUARIES AND DELTAS

The British region, compacted by the Caledonian movements, was during Devonian and Carboniferous times epeiric, in the sense that its uplifted portions were land undergoing erosion, and its depressed portions were at different times the sites of epeiric seas, estuaries, deltas and lakes in which great thicknesses of rock were deposited (p. 47). Only in the extreme south in Devonian times were geosynclinal conditions found.

We have already studied epeiric seas in the chapters devoted to the Jurassic and Cretaceous, and in the present section the only marine environments discussed are such as have not so far been fully illustrated in previous chapters. The major part of the section is devoted to coastal and continental environments; and here we have to deal with physiographical processes that in the main were very different from those which we have seen at work on the arid Hercynian continent (Section II), the difference being largely due to the prevalence of a more humid type of climate and more permanent rivers. The peculiar environment in which coal accumulated is discussed in detail.

The Section ends with reference to the beginnings of the Altaid orogeny, and to the gradual establishment towards the end of Carboniferous times of the dry continental environments with which our studies commenced in Part II.

CHAPTER XXIII

THE DEVONIAN SYSTEM

For the purpose of this book, the chief interest of the Devonian lies in the fact that it is the most ancient period in which we have any record of continental conditions preserved in fossiliferous strata. The Caledonian mountain-building which brought those continental conditions into being has been dealt with in the preceding chapter. In the present one emphasis will be chiefly laid on those physiographical features that were the outcome of the continental environment. But it must be recalled that it was only to the north of a line running roughly east and west through the present Bristol Channel that this environment was dominant. Its history is recorded in

what is usually designated the *Old Red Sandstone Facies*, formed in continental, lacustrine and coastal environments.[1] To the south of that line the *Marine Facies* or *Devonian*, sensu stricto, testifies to the existence of a *geosynclinal sea* that stretched eastwards into Belgium and Germany.

A. Old Red Sandstone Facies

By the Old Red Sandstone facies is implied a great series of red and green marls and sandstones, which in many parts contain coarse conglomerates, and in Scotland volcanic rocks also. In the north of Scotland there is in addition to the red sediments a great thickness of grey and black flags and shale. The Old Red Sandstone is usually unfossiliferous, but there are a number of horizons at which fish remains have been found, sometimes in great abundance. Occasionally Eurypterids and plants are also present.

Table XI gives the classification and characteristic faunas:

TABLE XI

Upper Old Red Sandstone, Farlovian [2]	*Holoptychius, Bothriolepis; Archanodon; Archæopteris* and other Carboniferous types of plants.
Middle Old Red Sandstone, Orcadian	*Coccosteus, Dipterus, Thursius*; and the primitive land-plants, *Rhynia, Hornea, Asteroxylon* (Fig. 131).
Lower Old Red Sandstone (2) Dittonian [2]	*Pteraspis* fauna, *Cephalaspis lyelli.*
(1) Downtonian	*Cyathaspis*, and *Thelodus* faunas, *Onchus, Eurypterids; Platyschisma, Lingula; Chonetes striatella, Orthis lunata.*

It will be noted that the Downtonian is here included as part of the Devonian, though usually ascribed to the Silurian. The grounds for this change are, as stated by Stamp, the abrupt introduction of new elements into the marine Silurian fauna, in particular the numerous fish and Eurypterids which are hardly known from the Lower Palæozoic. This was first made clear in France.[3] Stamp points

[1] J. Barrell, "The dominantly fluviatile origin under seasonal rainfall of the Old Red Sandstone," *Bull. Geol. Soc. Amer.*, vol. xxvii, 1916, pp. 345–86. See also note 1 on p. 293, note 1 on p. 294, notes 1 and 3 on p. 299.

[2] Term introduced by W. W. King, see L. D. Stamp's *Introduction to Stratigraphy*, p. 114. The term Dittonian is used here as equivalent to the Lower Old Red Sandstone or Caledonian of Scotland. Prof. Kiaer has informed the writer since the above was written that in his opinion and in view of the discoveries in Spitzbergen, the Dittonian of the Welsh cuvette is probably better regarded as the top of the Downtonian and older than the Caledonian.

[3] See Ch. Barrois, P. Pruvost, G. Dubois, *Mem. Soc. Geol. du Nord*, vol. vi, 1912–20, p. 161. L. D. Stamp, *Geol. Mag.*, vol. lvii, 1920, p. 164, and vol. lxi,

out also that the upper part of the Downtonian (as defined by the persistence of certain fish and Eurypterid genera) is composed of red marls and sandstones of the Old Red type, and in this portion the marine creatures found in the lowest Downtonian have disappeared, whereas the fish and Eurypterids persist.

The Old Red Sandstone facies is the sedimentary record of the continent that was brought into existence by the Caledonian movements in late Silurian and early Devonian times. The movements, however, continued throughout the Devonian with waning activity. Those parts of the continent that were uplifted were in general the scene of profound erosion that was acting under desert conditions (p. 295), for truly terrestrial vegetation had barely come into existence and was possibly still confined to lake-side swamps and water-courses. Many parts were mountainous and enjoyed an abundant rainfall, at any rate at certain seasons. Between the mountains lay intermont basins into which the detritus of the neighbouring land was washed, there to form the Old Red Sandstone.

The independent nature of the deposits of the several regions of Old Red Sandstone led Geikie [1] to recognize the following "lakes": Welsh Lake (South Wales to Welsh border, and Staffordshire to Shropshire); Cheviot Lake; Lake Caledonia (Central valley of Scotland, Arran and North Ireland); Lake Lorne (these three Scotch ones may be parts of one large cuvette); Lake Orcadie (Moray Firth to the Orkneys and perhaps South-West Norway). For our purpose, as already pointed out, it is convenient to consider the regions as cuvettes or basins of sedimentation (p. 79) rather than lakes, and accordingly to distinguish three, viz. Welsh, Caledonian, Orcadian, each with its distinctive history, written partly in the sediments and partly in the unconformities. The latter bear testimony to the renewal of the Caledonian movements in different districts at different times. The occurrences of unconformities and also the incidence of volcanic activity are set out in Table XII on next page, which hardly makes it clear that the Highlands had been uplifted before Downtonian times, though this is probable.

Both the Welsh and the southern parts at least of the Caledonian cuvette were at the beginning of the Downtonian epoch occupied by shallow arms of the sea; but these basins gradually lost their marine character, passing through estuarine or lagoon stages into a lacustrine

1924, p. 351. W. W. King and W. J. Lewis, *Proc. B'ham. Nat. Hist. and Phil. Soc.*, vol. xiv, 1917, p. 90. T. Robertson, "The Siluro-Devonian Junction in England," *Geol. Mag.*, 1928, pp. 385–400, marshalls the evidence in favour of the classification adopted here. Full references.

[1] A. Geikie on the "Old Red Sandstone of Western Europe," *Trans. Roy. Soc. Edinburgh*, vol. xxviii, 1878, p. 354.

or inland-sea condition which is indicated by the red colour and general similarity of the Upper Downtonian sediments to the Old Red Sandstone proper. Most of the Downtonian was therefore probably formed under conditions analogous to the Molasse of the Alpine region (see p. 175), in that its sediments were derived from uprising mountain-chains in basins that were the relics of the preceding geosynclinal seas, and occupied at times by the sea, at times by lakes.

TABLE XII

	Welsh.			Caledonian.					Orcadian.	
	Pembrokeshire.	Gower Peninsula.	Shropshire.	Cheviot.	Lanark.	Pentlands and Ayr.	Forfar and Stonehaven.	Lorne.	Mainland.	Islands.
Lower Carboniferous	C	C	C?	C	C	C	—	—	—	—
Upper O.R.S. . .	S & M		S	S	S	S	S	—	S	S & v
Middle O.R.S. . .	~	~	~	~	~	~	~	~	S	S & v
Lower O.R.S. { Dittonian	S	S	S	V+S	S+V	S+V	S+V	V+S	~	~
Lower O.R.S. { Downtonian	S	~	S+M	~	S+M	S+M	S+v	~	~	~
Silurian	M		M	~	M?	M	~	~	~	~

Explanation of Table

~ = Strata missing and uncomformity.
C = Carboniferous succeeds conformably.
S = Old Red Sandstone sedimentary facies.
V = Important, v Subsidiary, Volcanics; where V precedes S, the volcanic rocks predominate, and vice versa.
M = Normal marine strata.

In Scotland renewed folding also took place after Downtonian times, so that the true Lower Old Red (Caledonian) lies in most places unconformably on the Downtonian. It also oversteps that formation on to the older rocks, thereby indicating that the latter had by this time undergone the major part of their Caledonian deformation and concurrent erosion (Fig. 127). The conditions in the Caledonian area must be contrasted with those in the Welsh cuvette, where sedimentation proceeded uninterruptedly; and with the Orcadian region where apparently no important deposition took place until Middle Old Red Sandstone times.[1] The Orcadian Old Red is the only sedimentary record of that period.

[1] C. B. Crampton and R. G. Carruthers, "Geol. of Caithness," *Mem. Geol. Surv. Scotland*, 1914, p. 5.

The unconformity that everywhere exists below the Upper Old Red Sandstone testifies to great recrudescence of uplift and erosion, in which at many places thousands of feet of the lower divisions were planed off (see, for example, Fig. 127). When sedimentation was again renewed, apparently under fairly similar, though possibly more arid, conditions, there was a new and distinctive fish-fauna in the waters, and a new flora on the land. Some authors have

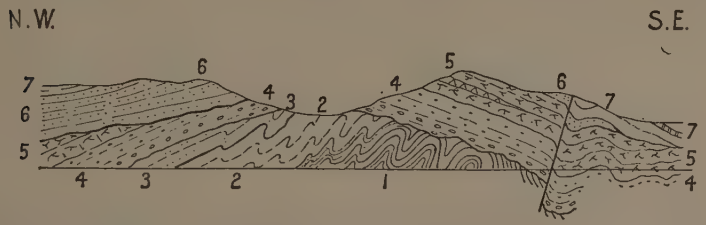


FIG. 127.—Diagrammatic Section across the Pentland Hills, by W. H. Laurie. 1, Wenlock; 2, Ludlow; 3, Downtonian; 4, Lower Old Red Sandstone; 5, Lavas of the Pentlands; 6, Upper Old Red Sandstone; 7, Carboniferous.

pointed out that since there is no break between the Lower Carboniferous and the Upper Old Red Sandstone [1] the latter might well be regarded merely as a basal member of the Carboniferous; but the physiographical environment seems to have differed markedly in the two formations, and for this reason the classification used here has gained universal acceptance.

In the chapters referring to Permian and Trias considerable space has been devoted to the processes of sedimentation under arid and semi-arid climates. Much that is written there would apply to sediments of the Old Red Sandstone facies, e.g. the discussions relating to the red colour, the rounding of sand-grains, the formation of torrential deposits, sun-cracks, the contemporaneous erosion of beds of marl laid down in sheets of water subjected to alternate desiccation and flooding, the formation of bone-beds, etc. Yet we must agree that though a desert-surrounding is suggested by many features of the Old Red Sandstone lithology, the desert nature may have been partly due to the limitation of vegetation to swamps and lakes; for the rocks, as a whole, show signs of abundant rainfall. Thus at fairly frequent levels fossil fish of many kinds occur, sometimes in abundance; and there are no known deposits of salt or gypsum to suggest that evaporation was in excess of precipitation. Geikie has interpreted the huge boulder conglomerates that occur near Oban and in other parts of Scotland as the shore deposits of the lakes; but many features in the conglomerates are more suggestive of an origin in the deltas of moun-

[1] Such a break does occur in Anglesey.

tain-torrents.[1] The picture that we get is that of large, more or less permanent lakes [2] in deep basins surrounded by mountains. Towards the margins of the lakes and, at times perhaps over their whole extent, sedimentation was in excess of the down-warping which corresponded roughly in amount to the great thickness of shallow-water deposits (in places the Lower Old Red is 16,000 feet thick). Under these conditions the lakes became shallow sheets of water or may have even disappeared, their place being taken by flood-plains and alluvial fans.

In the earlier part of the period, however, marine and estuarine deposits were laid down, which are also discussed in the sequel.

i. Caledonian Cuvette.[3]—In order to understand the nature of the Old Red Sandstone of the Caledonian Cuvette (Fig. 128) or, as Geikie termed it "Lake-basin," it is necessary to recall that it has a generally elongated shape following the Midland Valley of Scotland, but extended in bays and inlets beyond the present boundary faults of the valley (p. 281). As already pointed out, it is also possible that Geikie's Lakes Lorne and Cheviot may have been gulf-like extensions. Nevertheless the cuvette was determined in the main by the Caledonian movements, and its subsidence was controlled by their north-east to south-west trend. The marine conditions of the Downtonian, noted above, was followed by great earth-movements and the subsequent initiation of continental conditions in Central Scotland during the Dittonian.

The mountains over the Highlands must have been lofty chains from which descended rivers and torrents bearing heavy loads of coarse sand and pebbles. These sediments built out deltas, and were spread out on the lake-floor and in the bays and inlets. Here too are coarse boulder-beds, the stones in which are well-rounded, a feature that suggests that the streams were fairly permanent water-courses. For these reasons the thickness of the subdivisions is variable, and as a rule the oldest deposits occur within the Midland Valley where the basins were first initiated, the bordering inlets not becoming the site of sedimentation until later. The gradual sinking of the cuvette as time went on, together with changes in the terrestrial topography, accounts for the presence of littoral deposits at different horizons in different areas.

[1] See R. Campbell, *Trans. Roy. Soc. Edinburgh*, vol. lxviii, 1912–13, p. 954.

[2] Geikie points out that the area of his "Lake Caledonia" was comparable with, but probably exceeded, that of Lake Erie (Pres. Address Geol. Soc., *Proc. G. S.*, vol. xlviii, 1892, p. 68).

[3] A. Geikie, *op. cit.*, and *Ancient Volcanoes of Great Britain*, vol. i, p. 303. R. Campbell, *op. cit.*, and *Proc. Geol. Assoc.*, vol. xxiii, 1912, p. 299. G. Hickling, *Proc. Geol. Assoc.*, vol. xxiii, 1912, p. 302, and *Geol. Mag.*, 1908, p. 396.

The most remarkable feature of "Caledonian" Old Red times [1] was the opening up of numerous volcanic centres which built up vast piles of lava. The vents appear to have been, with some important exceptions, confined to the lake-basins, and to have avoided the neighbouring mountains; and the volcanic products are inter-bedded with the ordinary lake-sediments. The lavas often have cracks filled with sandstone or conglomerate, and had therefore been partially

FIG. 128.—Caledonian Intrusions and Devonian Vulcanicity in Scotland and Ireland.

Black = "Newer" or Caledonian Granites (except in Cheviots where it represents an Old Red Sandstone Granite); stipple, Old Red Sandstone Volcanic centres; 1, Forfarshire; 2, Ochil-Sidlaw Hills; 3, Pentlands; 4, Tinto; 5, Lanark-Ayrshire; 6, Kintyre; 7, Tyrone; 8, Oban; 9, Glencoe; 10, Cheviots; vertical ruling, land.

eroded before being covered. Many of the conglomerates in Kincardineshire are largely composed of pebbles derived from the lavas, a fact that proves that in places they were being vigorously denuded. Campbell has shown that volcanic piles existed to the north of the Highland Fault of which the sole evidence we now possess is the pebbles

[1] Volcanic activity had begun in Downtonian times in Kincardine (R. Campbell, *op. cit.*).

and boulders in the conglomerates south of the fault near Stonehaven. The vents that gave rise to these particular lavas must have lain to the north of the main Caledonian cuvette, but some seven other centres, ranging from Tyrone to Kincardine, as indicated on Fig. 128, lie in the region of maximum depression. Their linear arrangement, parallel to the Caledonian trend-lines, shows the close relations between their distribution and the orogenic movements. It is accordingly natural to find that the magma that fed the volcanoes belonged to the Pacific suite, and that the lavas are largely andesites and basalts; for this suite is characteristically associated with folded mountains (p. 16). The vents were for the most part non-explosive, for only rarely are agglomerates and tuffs of more than subsidiary importance if we compare their volume with the vast piles of lavas that from place to place reach thousands of feet in thickness. The vulcanicity was of the lava-plateau type (p. 15). In some districts the vents are indicated by cylindrical "necks" of agglomerate or tuff, piercing the lavas, but no doubt much of the magma reached the surface by fissure-vents (p. 15). After the volcanoes of the Midland Valley had become extinct, the basin still continued to subside and to be filled with detritus. Eventually uplift and folding supervened, and in places as much as 8,000 feet of rock were eroded away before the cuvette again became the scene of sandstone-accumulation in Upper Old Red Sandstone times. Possibly the lower part of these upper red sandstones with their wind-worn sand-grains may be accounted a desert-deposit, but the upper part was definitely formed in a freshwater lake in which fish abounded, and which was bordered by forests and swamps.

In the Lorne and Cheviot areas the volcanic rocks are accompanied by later plutonic and hypabyssal intrusions (p. 365), which have generally been classed with the so-called "Newer Granites" that occur in many parts of Scotland; but the bulk of the latter are earlier in date, for though post-dating the main tectonic movements, some of them had been laid bare in Lower Old Red Sandstone times, and provided pebbles for the conglomerates of that period.

ii. The Welsh Cuvette.[1]—The Old Red Sandstone of this cuvette now occurs from Shropshire and Staffordshire through the Marches of Wales to the South Wales Coalfield and Pembrokeshire. As already pointed out, the cuvette evolved from an arm of the Silurian sea; and the first-formed deposits are buff and grey sandstones and shales, with marine fossils predominating, though there are also remains of Eurypterids and fishes that probably lived in estuarine

[1] See particularly W. W. King, in "Geol. of Shropshire," *Proc. Geol. Assoc.*, vol. xxxvi, 1925, pp. 383–9. E. E. L. Dixon, "Geol. of S. Wales Coalfield," Part XIII (Pembroke and Tenby), *Mem. Geol. Surv.*, 1921, pp. 26–63.

or land-locked waters.[1] These passage beds are followed by a great thickness of red marls, and red and grey sandstones and cornstones in which, with very few exceptions, the fossils are fishes or Eurypterids. In general the rocks are fine-grained, and there are none of the coarse conglomerates and volcanic rocks so characteristic of the Caledonian cuvette, except in Pembrokeshire (conglomerates only) which was then near the margin of the cuvette. Also in contrast to the Caledonian development there is no unconformity below the Downtonian [2] nor between Dittonian above and Downtonian below; but everywhere in the cuvette the Upper Old Red Sandstone (Farlovian) is unconformable. These facts imply that there was no orogenic movement in this region until after the Dittonian had been deposited, though there was a continuous down-warping that kept pace with the deposition of the shallow-water sediments. There is considerable uncertainty as to the environment under which the Welsh-Shropshire Old Red Sandstone accumulated. In the first place it seems very doubtful (though it has been strongly urged) whether there was any persistent land-barrier between the cuvette and the sea which covered Devon and Cornwall; and without such a barrier a lacustrine origin would appear to be ruled out. There are however clear signs in the shape of false-bedding, ripple marks, sun-cracks, cornstones (see below) and contemporaneous erosion, that the bulk of the formation, excepting the lowest Downtonian, originated in very shallow basins that were frequently laid bare by the disappearance of the water; but the absence of salt and gypsum deposits suggests that the basins did not possess an internal drainage It has already been mentioned (note 1 below) that King regards the whole as marine, but J. W. Evans and E. E. L. Dixon take the opposite view.[3] It is conceivable that we are dealing with deposits laid down on coastal flats of the salt-marsh or "salina" type, where continental conditions usually prevailed. Often flooded at times of heavy rain, the flats may occasionally have been invaded by the sea; but such invasions were too short and too shallow for normal marine faunas to establish themselves. The rather wide distribution of fossil-fish at particular horizons may indicate periods of submersion, while the marls may have been formed from dust arrested by the water or by damp surfaces. Cornstones also suggest an arid or semi-arid climate. They are breccias formed of fragments of inorganic lime-

[1] King, however, regards these creatures as marine, but inhabiting very muddy shallow coastal seas, in which the ordinary marine forms could not live.

[2] Except in Pembrokeshire.

[3] J. W. Evans in *Handbuch d. Regionalen Geologie, British Isles*, p. 119. E. E. L. Dixon, *op. cit.* W. W. King, *op. cit.* King has found a supposed marine Lamellibranch, *Modiolopsis*, in association with Downtonian fishes in the Old Red facies.

stone, chips of shale and sometimes bits of the teeth, bones and dermal plates of fish, cemented by carbonate of lime into a hard bed rarely more than a few inches thick. Each cornstone probably denotes the contemporary breaking up of thin limestones and films of mud on the bottoms of pools that periodically dried up, the debris being subsequently washed together by the next flood. They are thus comparable in origin to the marl-breccias or pellet-rocks of the Upper Carboniferous, Permian and Trias (p. 86).

It is the cornstones that afford most of the fossil evidence except in the lower part of the Downtonian, where "bone-beds" (p. 132) occur. One of the latter in particular, known as the Ludlow Bone Bed, is recognized over a very wide area, and is taken to mark the base of the whole system on the method of classification adopted here.

The remarkable identity of many of the genera and even of the species of fish in the Welsh and Scotch Downtonian developments suggests that the two cuvettes were covered by the same sea or else were drained by rivers that flowed into the same sea; for it is quite possible that the Devonian fish, like the present-day salmon, were able to live in fresh or salt water, and to have thus made their way into regions that geographically were otherwise isolated from one another.[1] In support of this view it may be remarked that a number of them have been occasionally found in undoubted marine deposits.

iii. The Orcadian Cuvette.[2]—The Geological Survey Memoir on Caithness by C. B. Crampton and R. G. Carruthers has given us a very clear picture of the processes of sedimentation in the Orcadian Cuvette and glimpses of the denudation that was going on round the shores of the lake or lakes that covered its lowest parts. The following account is based on their memoir.

As already noted (Table XII) this region has a development of Upper Old Red Sandstones resting unconformably upon an older series of conglomerates, breccias, sandstones, flagstones and mudstones amounting to 16,000–18,000 feet in thickness. Of these the coarse red sediments in the lowest part are barren, but the great series (11,000–12,000 feet thick) of grey and dark flagstones, mudstones and limestones known as the Caithness Flags have yielded a peculiar fish-fauna that is regarded as indicating a Middle Old Red Sandstone (Orcadian) age. The highest beds are again sandstones, yellow and reddish in colour, and known as the John-o'-Groats Sandstone.

[1] Mr. King informs me that many of the Shropshire genera are found in Norway and Spitzbergen. See also J. Kiaer, "The Downtonian Fauna of Norway," *Vid. Selsk. Skrifter*, Oslo, 1924, No. 6.

[2] A. Geikie, "On the Old Red Sandstone of Western Europe," Pt. I, *Trans. Roy. Soc. Edinburgh*, vol. xxviii, 1878, pp. 368–449. C. B. Crampton and R. G. Carruthers, "Geol. of Caithness," *Mem. Geol. Surv.*, 1914.

This great pile of strata was laid down unconformably on an irregular hilly landscape cut out of the schists, quartzites, gneisses and granites of the Highlands (Fig. 129); and accumulated in one, or possibly two, large depressions, the lower parts of which were covered by the waters of a freshwater lake or lakes. The hill-slopes were mantled over by screes, and around the margins of the lakes, delta and flood-plain deposits (now breccias, conglomerates and arkoses) merged into the true lacustrine sediments of the deeper

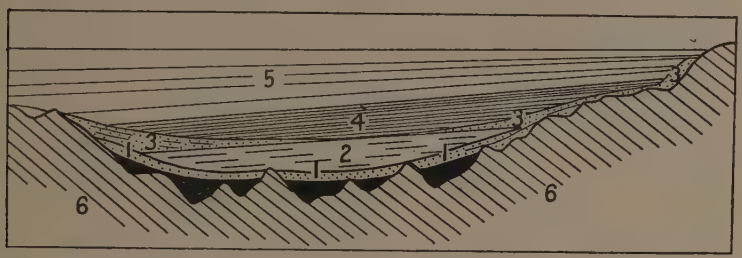


FIG. 129.—Section across the Orcadian Cuvette, based on the Geological Survey Memoir.

Full black, breccias and mudstones of the hollows on the old land-surface of pre-Devonian schists and granites (6). 1, Upper breccias and conglomerates; 2, Helman Head Beds; 3, Red Beds; 4, Wick Flags; 5, Thurso Flags (2–5, Caithness Flags).

sheets of water (now flagstones and mudstones). Great fluctuations in the area of the lakes took place during the formation of these rocks, shrinkage being represented by an extension of the delta and flood-plain deposits across the bed of the lake. As the latter expanded again, the area covered by the flagstone type of sediment increased, and there appear in the deposits signs of a deeper-water origin. Despite these fluctuations, the nature of the fossils and the absence of salt and gypsum indicate that the lake-waters were always fresh, and the lakes therefore had permanent outlets. Table XIII gives the main subdivisions of the formation, and indicates for each stage the general nature of the environment which will be more fully described in the sequel.

TABLE XIII

3. *John-o'-Groats Sandstone.* Yellow and reddish, false-bedded sandstone.	Contraction of the lakes, dry climate and possibly subaerial deposits.
2. *Caithness Flags.* Grey and dark flagstones with one large intercalation of red beds.	Great expansion of the lakes or lake, both before and after a drier episode represented by the red beds. Abundant life. Climate probably less arid than in 1.
1. *Barren Red Beds.* Red conglomerates, breccias, arkoses, sandstone, and barren mudstones.	Lakes small and probably numerous, in hollows. Semi-arid climate. Torrential delta and flood-plain deposits and screes.

1. *Barren Red Beds.*—It will be readily understood from what has already been said and from an examination of Fig. 129 that the earliest deposits of the Orcadian Cuvette were the screes, and alluvial cones and fans that mantled over the hilly landscape of granites and Highland rocks. These deposits are mainly red breccias and arkoses. The fragments in the breccias vary greatly with the type of rock in the underlying platform, and are evidently of local origin. In between the old hills lay more or less separate basins in some of which excessively fine mudstones were deposited with intercalations of gritty arkose. It is thought that the wind was probably responsible for the segregation of the coarse and fine sediment into separate layers. The characteristics of semi-arid deposits have already been fully discussed so that the red colour, fresh nature of the felspars, the abundance of coarse angular detritus need not be further commented on. It is significant, however, to note that whereas the Caledonian Old Red Sandstone has 70 to 80 per cent of its felspars kaolinized, in the Orcadian Barren Red Beds 70 to 90 per cent are fresh. The difference in climate suggested by this, supplements the evidence of the fish-faunas that the two developments were not formed contemporaneously.

This earliest stage in the Orcadian Cuvette was followed by one in which the geography was in some way different, for great fans of breccia and arkose were washed into the cuvette by torrential rivers and spread out in an almost continuous thick sheet over all the preceding deposits where they existed and mantled over the lower slopes where they did not. These are the Upper Breccias and conglomerates, forming the upper part of the Barren Red Beds (Fig. 129, 1).

2. *Caithness Flags* (Fig. 129, 2–5).—These two early stages recall the type of sedimentation and environment that obtained over the English Midlands in Permian and Triassic times, and over the North-west Highlands in the Torridonian period; but the great Caithness Flagstone Group which succeeds them presents a type which is unique in these islands. With one large intercalation of red beds in its midst (Fig. 129, 3), it attains a thickness of 11,000–12,000 feet, and consists for the most part of grey, evenly-bedded, fine-grained flags, mudstones and limestones, often dark with organic matter. These flagstones are regarded as the deposits of Lake Orcadie, which was a shallow sheet of water far greater than any that up to this time had existed in the cuvette. The intercalated red beds represent a shrinking of this lake and a return of the marginal torrent-fan type of sedimentation; but apart from this there is much evidence that the lake frequently dwindled into isolated sheets of water, and its bottom over vast areas became mud-flats that dried out

and cracked into polygons under the heat of the sun. This is recorded by mud-cracks filled with sand or with curved fragments of calcareous shale which are taken to be curled-up bits of the baked skin formed on the surface of the mud as it dried. In modern deserts such broken up mud-pellicle is often blown about by the wind; and this may have been the case here also. Possibly some of the beds in which fossil fish are so abundant also record the drying up of the waters and the death of all the denizens. At times of desiccation the water collected in hollows into which the streams that crossed the mud-flats bore a washing of a fine gritty silt and bits of fish scales and plants (Ackergill Beds). In one part through a considerable thickness there is a recurrence of beds with ripple-marked surfaces. The ripples, being almost always oriented N.W.–S.E., indicate the constant direction of a current of water or of wind throughout a great length of time. At another level the ripple-marks cross one another, a feature denoting an origin in very shallow water.

At two places we catch a glimpse of the actual shore of the lake. At the first, even-bedded flagstones abut against an almost vertical wall of granite and gneiss. "A few feet from the vertical junction, small highly angular fragments of granite and chips of fresh felspar lie scattered in the muddy sediment. They were evidently dislodged by subaerial flaking of the rock. . . . There was nothing here of the nature of a beach, nor was there any tidal scour."

At the other place—not far away—we can see a fan-shaped mass of tufa that was evidently laid down by a stream that here entered the lake. Heavily charged with lime the brook had deposited the tufa over its channel and banks, just as may be seen in any limestone district to-day (e.g. the "Petrifying Springs" at Matlock). At times the tufa was mingled with a wash of stones that now show as intercalated calcareous breccia.

The large amount of black organic matter in the Caithness Flags and the general absence of recognizable plant-remains is best interpreted as implying an abundance of planktonic micro-organisms (Protophyta and Protozoa), which would no doubt form the ultimate food-supply for the fish. That the adjacent land supported a lowly type of vegetation is demonstrated by the remarkable discoveries at Rhynie dealt with on p. 305.

Sedimentary Rhythms.[1]—Many parts of the Caithness Flags display a repetition of certain lithological types in a particular order, such as is shown in Fig. 130. There are minor differences in these sedimentary rhythms in different portions of the whole sequence; but the repetition has no doubt the same significance throughout; and is connected with fluctuations in the level of the lake and in the

[1] See J. Barrell, *Bull. Geol. Soc. Amer.*, vol. xxviii, 1917, pp. 776–809.

supply of detritus. Taking the example shown in Fig. 130, the black slaty flags and limestones are regarded as recording the relatively deep, still waters of a high-level phase of the lake. The shallowing of the water and increase of the supply of coarser detritus is shown by the appearance of sandy layers in the flags, followed by a thick bed of sandstone. Finally we see a low-level phase of the lake recorded by sun-cracked mudstones. After this the water rose again, and the

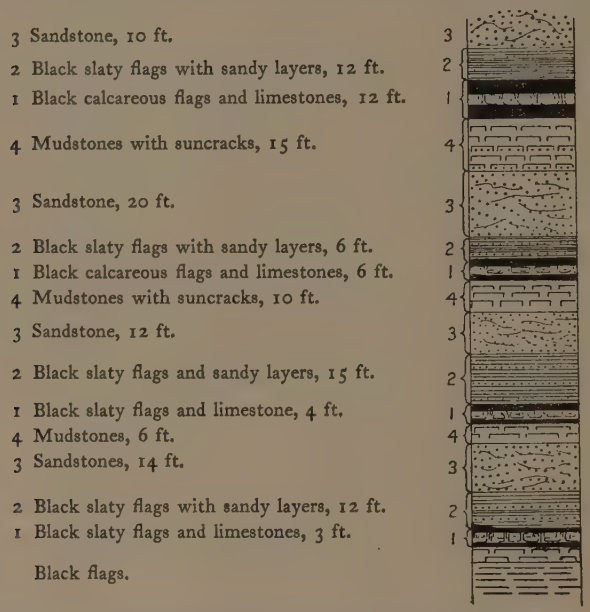

3 Sandstone, 10 ft.
2 Black slaty flags with sandy layers, 12 ft.
1 Black calcareous flags and limestones, 12 ft.
4 Mudstones with suncracks, 15 ft.
3 Sandstone, 20 ft.
2 Black slaty flags with sandy layers, 6 ft.
1 Black calcareous flags and limestones, 6 ft.
4 Mudstones with suncracks, 10 ft.
3 Sandstone, 12 ft.
2 Black slaty flags and sandy layers, 15 ft.
1 Black slaty flags and limestone, 4 ft.
4 Mudstones, 6 ft.
3 Sandstones, 14 ft.
2 Black slaty flags with sandy layers, 12 ft.
1 Black slaty flags and limestones, 3 ft.
Black flags.

FIG. 130.—Sedimentary rhythm in the Caithness Flags.
After *Mem. Geol. Survey*, "Geology of Caithness," 1914. By permission of the Controller of H.M. Stationery Office.

succession of events was repeated. In one case a particular sedimentary rhythm can be seen to recur almost without intermission throughout 500 feet of flags.

There is no suggestion made in the memoir as to whether the repetition can be correlated with contemporary earth-movements, the existence of which is repeatedly referred to; or whether it corresponds with some periodic change of climate due to astronomical causes. The existence of two different types of climatic cycles appears now to be well-established. *Brückner's Cycle*, averaging 35 years, and composed of a series of cold wet years followed by a series of hot dry ones, seems too short to account for the thickness of sediment found in each rhythm; and the longer *Milankovitch cycle* varying between

20,000 and 90,000 years,[1] may perhaps be too long, yet appears a possible cause of the sedimentary rhythm in the Caithness Flags.

3. *The John-o'-Groats Sandstone.*—The last stage of the Middle Old Red is represented by the John-o'-Groats Sandstone whose lithological characters suggest that the lake had shrunk enormously or even disappeared, and that its place had been taken by sand-dunes or by delta-fans fed by ephemeral streams.

Devonian Life.

The life in and around the Old Red Sandstone lakes has a peculiar interest to us, for it included the stocks that were the forerunners of the land fauna and flora from which the present-day terrestrial creatures have ultimately been derived. Some have claimed that the Devonian fish and Eurypterids had arisen in freshwaters of which we have no record in the older periods, and first migrated into the sea at the beginning of the Devonian age; while others regard them as marine groups that became important fossil-forming types about this time. The latter view demands the adaptation of the fish first to estuarine and later to freshwater habits. Amongst the Old Red fishes we find heavily-armoured Ostracoderms, primitive Elasmobranchs, and certain Dipnoans, the modern representatives of which last class are equipped with organs for breathing either under water or in air. It has been suggested that in the Devonian they were similarly provided with a means of preserving life through a period of desiccation of the water in which they usually lived, and that this adaptation to a terrestrial existence later made possible the invasion of the land by the vertebrates.[2] From this point of view, as a terrestrial vertebrate, man may look on the Devonian as the first great milestone on the road of human evolution.

The Devonian appears also to have seen the origin of a land-flora. True, there were algæ and bacteria before those days; but the earliest known plants, the detailed structure of which declares them as terrestrial, are found in the Lower Old Red Sandstone. Near Brecon in South Wales there have recently been discovered leafless and rootless stems arising from rhizomes, and presenting very primitive characters.[3] These plants are, however, not so well-known as those from the now famous Rhynie Chert Bed near Aberdeen whose age is probably

[1] Due to variation in the amount of the sun's radiation received by the earth as a result of the variation of the heliocentric length of perihelion, the obliquity of the plane of the ecliptic, and the eccentricity of the orbit of the earth (see W. Köppen and A. Wegener, *Die Klima der geol. Vorzeit*, Berlin, 1924, pp. 205–17).

[2] This view may require revision, as a footprint of a terrestrial vertebrate has now been found in the Devonian of the U.S.A. R. S. Lull in *Evolution of the Earth and of its Inhabitants*, 1923.

[3] A. Heard, *Q.J.G.S.*, vol. lxxxiii, 1927, pp. 195–209.

Middle Old Red Sandstone.[1] The chert is a silicified peat largely consisting of small, very primitive vascular plants (Fig. 131), known as *Rhynia* and *Hornea*. Associated with them is *Asteroxylon* (a slightly more highly organized plant), and a number of minute terrestrial, air-breathing arachnids (mites? spiders, anthracomarti, etc.).

FIG. 131.—Hornea Lignieri and Asteroxylon Mackiei.
After Kidston and Lang, *Trans. Roy. Soc. Edinburgh, loc. cit.*

The silicification, perhaps due to the siliceous waters of a hot spring or fumarole, has preserved every detail not only of the arachnids and plants, but even of the funguses that lived amongst the decomposing vegetation.

[1] R. Kidston and W. H. Lang, *Trans. Roy. Soc. Edinburgh*, vols. li and lii, 1917–21. S. Hurst, *Annals and Mag. Nat. Hist.*, ser. 9, vol. xii, 1923, pp. 455–474.

The simple nature of the Rhynie plants contrasts vividly with the variety and high state of structural development displayed by the vegetation of the Upper Old Red Sandstone, which contains many elements of the well-known Carboniferous flora.[1]

It is clear that from the very humble beginnings in the earlier part of the period plants had made great advances by its end; and that any indications of a desert-environment provided by the Upper Old Red Sandstone must be due to aridity rather than to non-existence of vegetation.

The expansion of the terrestrial flora and its colonization of the land-surface must have had a profound influence on the processes of erosion and the rate at which they operated, and on the composition of river and sea water.[2]

B. Marine or Devonian Facies

The physiographic environment in which the Devonian of Devon and Cornwall came into being was that of a geosyclinal sea; but North Devon lay on the continental shelf, and at times received red sand deposits of the Old Red type, at other times marine sediments. To some extent, therefore, North Devon affords a link between the continental and the marine facies. At present the Devonian outcrops in two broad belts running east and west, separated by a synclinal region composed of Carboniferous strata. Both systems were involved in the Altaid orogeny (p. 71), and have suffered an enormous amount of plication and minor thrusting, so that the true sequence and the mutual relationships of the different subdivisions are not always clear. The fuller succession and clearer arrangement in Northern France, Belgium and Germany have however provided a standard of comparison for the English sequence, since many of the fossils are common to the two regions. Accordingly it is now possible to correlate with fair accuracy the Devonian on the south of the Carboniferous syncline with that on the north, and to show that these marine deposits are contemporary with part of the Old Red Sandstone facies farther north. The latter correlation has been rendered possible by the occasional occurrence of Old Red Sandstone fishes as fossils in the marine beds or in estuarine deposits intercalated with them. Table XIV expresses these relations.

[1] In Upper Old Red Sandstone times the first-known freshwater mollusca also appear.

[2] See R. A. Daly, on "The Evolution of Limestones," *Bull. Geol. Soc. America*, vol. xx, 1909, pp. 153–70.

TABLE XIV

	Belgium.	O.R.S. Fish fauna.	Cornwall and South Devon.	North Devon.	Welsh Cuvette.
Upper	Famennian	*Holoptychius*	Green, black and red slates	Pilton Beds	Farlovian; Farlow Sandstone (Salop), and Skrinkle Sandstone (Pembroke)
	Frasnian	*Bothriolepis*		Baggy and Marwood Beds Pickwell Down Sandstone Morte Slates	
			Torquay–Plymouth Limestone	Ilfracombe Beds	
			Ashprington Volcanic Series		Unconformity
Middle	Givetian	*Coccosteus*	Hopes Nose Limestone	Combe Martin Beds	
	Couvinian		Staddon Grits	Hangman Grits	
Lower	Coblenzian	*Pteraspis* *Cephalaspis*	Meadfoot Beds Dartmouth Slates and Watergate Bay Beds	Lynton Slates Foreland Grits	Dittonian
	Gedinnian	*Cyathaspis* *Thelodus*	—	—	Downtonian

Having devoted Chapter XXI to a discussion of a geosynclinal environment, it is unnecessary to enter deeply into a study of a similar environment as displayed by the Devonian. It may however be pointed out that in the small portion which falls in Britain, the geosyncline shows several typical features; e.g. conditions were at times favourable for the building up of reef-limestones, the volcanoes that broke out on the sea-floor emitted spilites and pillow-lavas, and finally the geosynclinal deposits were involved in the next succeeding orogeny, and were invaded by the granite masses of Cornwall and Devon. It seems probable that the geosynclinal sea in this case was of the *liminal* type [1] (p. 47), the deposits being laid down on the continental slope and not in an inter-continental sea, as in the case of the Caledonian and Alpine Geosynclines.

[1] J. W. Evans, *Q.J.G.S.*, vol. lxxxii, 1926, p. lxxvi. Here also is a fuller examination of the nature and subsequent history of the geosyncline.

CHAPTER XXIV

THE CARBONIFEROUS SYSTEM: SHALLOW SEAS, REEFS, LAGOONS, DELTAS AND ESTUARIES

The long and diversified history of the Carboniferous period yields examples of many types of physiographical environments and processes, but attention will here be focussed on a few only, which are not adequately exemplified in other British strata. The stratigraphy of the period will only be dealt with in outline.

The formation can conveniently be divided into:

Upper or Westphalian	Coal Measure Series:	Essentially estuarine swamp deposits.
	Millstone Grit Series:	Essentially deltaic deposits.
Lower or Avonian	Carboniferous Limestone Series:	Essentially marine deposits.

A fuller classification is given in Table XV (opposite).

General Outline of the Geography of the Carboniferous.

The close of the Old Red Sandstone period saw the Caledonian continent reduced to gentle uplands, plains, and silted-up lake-bottoms, and thus ripe for a new invasion by the sea that lay to the south. The great northern continent (Atlantis) remained unsubmerged, but the sea encroached upon most of the British area during Avonian times. A promontory or island (St. George's Land), the forerunner of the Mercian Highlands (p. 79), lay from Wales across the Midlands, and separated a southern and south-western province which was invaded in Tournaisian times from a central and northerly one, only a small part of which came under marine conditions until Upper Viséan times [1] (Fig. 132*a*).

[1] K. M. Booker and R. G. S. Hudson, *Proc. Yorks. Geol. Soc.*, new series, vol. xx, 1926, p. 434, place the development north of the Craven Fault (p. 317) in the Northern, and the development in the Craven Lowlands, Derbyshire area, and Dublin area in the Central Province.

TABLE XV

(See Plate I B.)

	Time divisions.	Rock formations.
Upper Carboniferous or Westphalian (sensu lato)	Radstockian *	Productive coal measures (Somerset and ? South Wales). ? Barren red measures (Midlands).
	Staffordian	Productive coal measures, partially-productive sandstones ("Pennant") and some red measures in South Wales. Mainly barren, and partly red, measures in Midlands. ? Red measures in north of England and Scotland.
	Yorkian	Productive coal measures, ? including some "Pennant" in South Wales. ? Middle and Upper "Culm" in Devon.
	Lancastrian	Millstone Grit Series, grits, shales, occasional coals.
Lower Carboniferous or Avonian	Viséan (Upper C, S, and D zones)	Upper Mountain or Carboniferous Limestone, including Culm in Devonshire, Pendleside and Yoredale Beds in north of England, and coal- and oilshale-bearing rocks in Northumberland (Bernician) and in Scotland (Scottish Carboniferous Limestone Series).
		Scotch Puy-Volcanoes.
	Tournaisian (K, Z, and lower C zones)	Lower Mountain or Carboniferous Limestone, including sandy and cementstone-bearing rocks in Northumberland (Tuedian) and in Scotland (Calciferous Sandstone Series).
		Scotch Plateau-Volcanoes.

* The Radstockian Coal Measures and the highest part of the barren Upper Coal Measures may be Stephanian, not Westphalian.

Lower Carboniferous.—The Avonian sea appears to have been shallow and in general clear: consequently limestone is the most characteristic rock-type, attaining in some districts to many hundreds of feet in thickness. Scattered over the sea-floor in places were reef-like mounds, comparable in some respect to the recent coral-reefs. There were, however, areas that at times were muddy, in which accumulated dark shales alternating with either thin or thickish bands of limestone or sandstone. The Pendleside and Yoredale Beds are of this type (Fig. 132 *a*).[1] The fossils found in them are

[1] The former is characterized by a marine facies with Goniatites, the latter by distinctive marine fossils in some of the shales and limestones and by the frequent occurrence of sandstones and coals that show a deltaic origin.

generally different from those of the massive limestone, and considerable difficulty has been encountered in correlating the three facies. In general, however, it will be noted that the muddy facies is best developed in the Pennine region. As the Avonian is traced from here through Northumberland into the Midland Valley of Scotland, the facies gradually changes by the introduction of more sandstones and cementstones, and by the appearance of beds of coal.

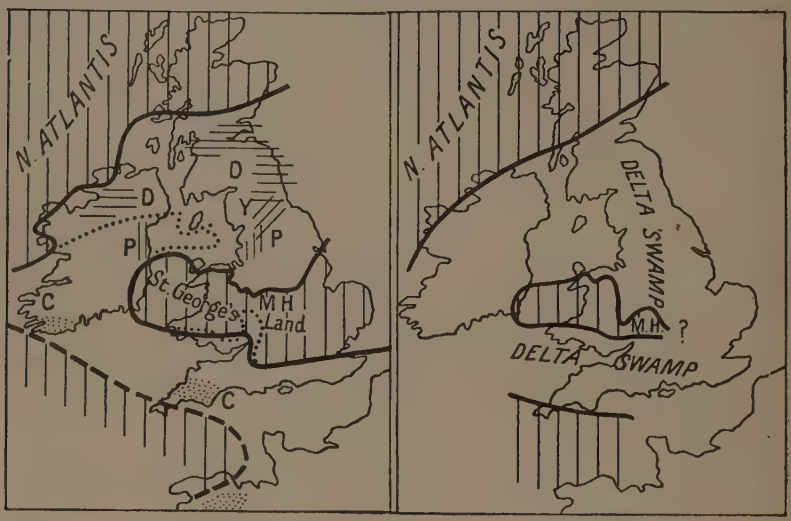


FIG. 132.

a. British region in Upper Avonian times (*Dibunophyllum* zone); land, shaded, showing the approximate distribution of certain facies, viz., D, delta-swamp; Y, Yoredale; P, Pendleside (with Goniatites); C, Culm; elsewhere limestones predominate and these are interbedded with the other facies at times. Line of dots, coastline of early Avonian Sea.

b. Coal Measure Geography. M H, Mercian Highlands.

It is clear that this region was nearer to the continent from which the detritus was being derived, and the seams of coal with their underlying "seat-earths" or "under-clays" are held by some to represent actual delta-flats on which the coal-making plants lived and died, and by their debris built up peats which are now the coals of the Bernician Series of Northumberland and of the Edge Coal group in the "Scottish Carboniferous Limestone Series."[1] The alternations of marine limestones and shales with the coals in the Avonian of Scotland show that at times subsidence proceeded so fast that the sea invaded and overwhelmed the peat-swamps, which

[1] Some of the coals may have been formed of material drifted to its present site.

again came into being when the surface had been built up to sea-level. This northernmost region of the Avonian Sea was also the site of a very extensive vulcanicity of two types. At first vast lava-plateaux were built up in several districts without much explosive violence. At a slightly later date a great number of small puy-volcanoes, emitting chiefly tuff and ashes were scattered over the Avonian Sea in South Scotland. The volcanic processes there illustrated are discussed in Chapter XXV. Other volcanoes were active in Cumberland and Derbyshire.

In Plate I B an attempt has been made to illustrate in the form of a section along a line roughly from Bristol to Birmingham, and thence almost due north to Edinburgh, the lithological changes and the continued subsidence of certain regions.

Upper Carboniferous.—If we bear in mind the evidence for open seas in the south-western and western parts of Britain, and for the shallow seas and deltas of Northern England and Scotland which merged into the low coastal plain of the northern continent, it is fairly easy to imagine how the geographical environment of the Avonian developed gradually into that of Upper Carboniferous times.

At the end of Avonian times there were in several districts gentle earth-movements [1] and erosion. In these areas the Millstone Grit Series (Lancastrian) succeeds unconformably, but in other regions there seems to be no break. The Millstone Grit Series of the Pennines represents strata laid down in a great river-delta and in the seas adjacent to it. It consists partly of coarse sandstones and grits, on the top of some of which lie coal seams, and partly of dark-coloured shales, many of which are marine and contain Goniatites of zonal significance, while others are probably freshwater in origin.

These coarse delta-deposits and intervening shales can be traced into North Wales where the formation is predominatingly shaly.[2] The so-called Millstone Grits of North Wales and Forest of Dean do not appear to be contemporary with the true Millstone Grit of the Pennines, but to be rather of Avonian age. Those of the South Wales coalfield, however, are post-Avonian and possibly contemporary with the Pennine development, though formed in an independent cuvette.

In the Pennine Region the Coal Measures proper (Fig. 132*b*) succeed the Millstone Grit conformably, but there is always a sudden cessation of the coarse sandy material and an alteration in the nature of the finer sediments. Perhaps subsidence of the northern con-

[1] S. H. Reynolds, *Rep. Brit. Assoc.*, Oxford, 1926, pp. 79–80.

[2] W. B. Wright and others, "Geol. of the Rossendale Anticline," *Mem. Geol. Surv.*, 1927, p. 127.

tinent had caused the coarse deltaic materials to be retained farther to the north. In any case a great extension of the swampy peat-morasses took place, and we may picture a huge region practically at sea-level covered with dense vegetation growing on peat or on mud-flats and sand-banks, and intersected by the distributaries of the northern rivers that made their meandering ways across it. But a gradual subsidence more or less kept pace with the accumulation of sediment (Plate I B). When the movement proceeded too rapidly the sea sometimes spread far and wide over the delta, and left its record in fossiliferous muds that we now know as "Marine Bands" (p. 339). When the downward movement was slightly less the swamp was flooded by fresh water, and the peat was buried below estuarine muds; but when deposition and subsidence were exactly balanced the growth of peat went on uninterruptedly. The thickness of peat required to make even a moderate coal seam is staggering, when it is realized that a lump of coal has perhaps not more than 5 per cent of the original volume of the peat from which it has been derived.[1] On this estimate 600 feet of peat would be required to provide the "10 yard" or "Thick Coal" of South Staffordshire (p. 337).

The northern delta with its coal swamps now covered all England as far south as the Mercian Highlands (latitude of Birmingham); and the Coal Measures of the Bristol, South Wales, and Kent fields though accumulated under similar conditions were, it is believed, the delta-deposits of another system of rivers, about which little is known (Fig. 132 *b*).

In the closing phases of the Carboniferous the scene again changes. In the Midlands the Staffordian strata record a great change in climate and in the distribution of land and sea, a change which caused the delta-swamps to dry up and give place to inconstant sheets of water fed by the equally inconstant torrents from arid deserts. Here too the rocks record but little change of environment as we pass upwards into the Permian (Chapters VI and VII). In South Wales, Bristol, and Somerset coal-forming conditions persisted, coarse deltaic deposits being at times laid down (Pennant Series), while at other times finer sediment alone reached the district. In most other parts of the country, however, erosion marked the close of the Carboniferous period, as is particularly clearly recorded by the sub-Permian unconformity in the Pennine region (p. 94).

[1] See P. F. Kendall and H. E. Wroot, *G. of Y.*, p. 147 and R. Thiessen, *U.S. Bureau of Mines Bull.*, 117, 1920, pp. 51–2. Thiessen's method of estimating the reduction is a direct one based on the measurement of uncompressed and compressed cells in woody tissue. The greatest linear reduction observed by him was in the ratio of 40 to 1.

Evidence of Shallow-water Deposition.

It is perhaps surprising that it is possible for a thick and widespread limestone formation to be built up in water of small or, at most, of moderate depth. Yet this appears to have been the case with the Carboniferous Limestone. Despite its great thickness and its extension from Belgium westwards to Ireland and northwards to Scotland, the more its lithological features are studied, the clearer it is that the great bulk of the limestones originated at no great depth. A number of different shallow-water facies have been recognized by Dixon and Vaughan in the Gower Peninsula,[1] and by Garwood [2] in the north of England, and similar rocks elsewhere confirm the general statement made above.

By no means less striking is the evidence for shallow-water surroundings afforded by the reef-limestones and algæ-limestones in the north of England (p. 316). It is perhaps unnecessary to remind the reader that in all these cases the great thickness of shallow-water sediments denotes a gradual depression of the sea-floor during their formation.

Lagoon-phases.—An extremely shallow-water facies has been discussed by Dixon under the name of "lagoon phase" [3] which he defined as follows: "By a lagoon-phase is meant a group of rocks, the characters and development of which show that it has been deposited in a coastal area, of wide extent both parallel and at right angles to the coast, but so extremely shallow as to have been, in effect, isolated from the neighbouring though deeper parts of the sea, and thus to have become the site of peculiar types of sediment and fauna." He points out that the rock-types indicate an absence of currents and tidal effects that is probably due to a partial barrier between the lagoon and open sea. This would account for the existence of impalpable calcareous muds, now chinastone-limestones or "calcite-mudstones"; hæmatitic limestones; purple and green shales; detritus-free shallow-water cherts; oolites and pisolites (p. 146); beds of fragments of contemporaneous sediments; and for the distinctive shallow-water fauna. The lithological characteristics of the so-called lagoon-phase first described in the Gower Peninsula (South Wales) are found in many other districts.

[1] E. E. L. Dixon and A. Vaughan, *Q.J.G.S.*, vol. lxviii, 1911, pp. 511–31.

[2] E. J. Garwood, *Q.J.G.S.*, vol. lxviii, 1912, pp. 449–586.

[3] Dixon's selection of the word lagoon in this sense is unfortunate because, although coral-reef lagoons may provide the environment he envisages, yet many coastal lagoons are muddy and bordered by swamps and vegetation; and the carbonaceous shales of the Coal Measures probably arose in such an environment (p. 325), but are not a lagoon-phase in Dixon's sense.

In the north of England Garwood found another type of shallow-water facies, in which calcareous algæ had functioned as important rock-builders. The limitation of algæ to the sunlit upper waters of the sea is so rigid that rocks owing their existence to these plants must have been formed in extremely shallow water.

Reef-Knolls.—In the record of the rocks there are few examples of the functioning in the past of a physiographical control which can be studied in the world of to-day, that appeal to the imagination with greater force than do the reef-like thickenings occasionally observable in the Devonian, Carboniferous and later limestone formations. Sometimes, as in the Corallian (p. 150), a dome-like mass of limestone occurs more or less surrounded by argillaceous strata, but in the Avonian of Lancashire and Yorkshire thick masses of singularly pure limestone (the thickest recorded in Lancashire is 1,400 feet), often devoid of bedding, pass laterally into less pure, bedded limestones of quite a different type. Not only do they differ in lithological appearance, but the numerous fossils that they contain, more particularly the brachiopods, molluscs, and corals are also distinctive. The type of limestone and of fauna go together so consistently that they are regarded as constituting a "Reef-knoll" facies, adopting the name first applied by Tiddeman [1] to these thickened masses of limestone which almost invariably express themselves at the surface as rounded knolls (Fig. 133). He regarded them as analogous to a modern coral reef (p. 50), for although the types of animals that build reefs to-day differ from those of the Carboniferous Limestone seas, yet the reef-knolls resemble modern oceanic reefs in the following particulars: the lithological and palæontological facies differs from that of the surrounding rocks; the reef-limestones are thicker, purer, and less bedded than the surrounding rocks; and often contain dolomites, Bryozoan limestones, and tufa-like limestones; near the sides of the reef-knoll there are sometimes breccias that represent the talus of wave-broken blocks from the fringe of the reef.

In three districts in Lancashire and North-West Yorkshire [2] reef-knolls are developed, and amongst them are reefs of three distinct ages (Plate 1 B). This suggests that reef-building took place over a great length of time whenever conditions were suit-

[1] R. H. Tiddeman, *Rep. Brit. Assoc.*, 1889, p. 600; 1900, pp. 740–42. D. Parkinson, *Q.J.G.S.*, vol. lxxxii, 1926, p. 223. E. J. Garwood and E. Goodyear, *Q.J.G.S.*, vol. lxxx, 1924, pp. 229–58. K. M. Booker and R. G. S. Hudson, *op. cit.*

[2] Similar reefs are known in the Avonian of Belgium under the name of Waulsortian, and from a number of different British districts (see S. H. Reynolds, *Rep. Brit. Assoc.*, Oxford, 1926, pp. 88–9).

able.[1] It is noteworthy that all the principal occurrences lie south of the Craven Faults [2] in a region which was one of long-continued and more rapid subsidence than obtained to the north of the faults, where reef-knolls are almost unknown (Plate I B). This is interesting as evidence in support of Darwin's theory of the origin of oceanic coral-islands, which has been called into question by many writers [3] (p. 52); for it seems clear that the Carboniferous Lime-

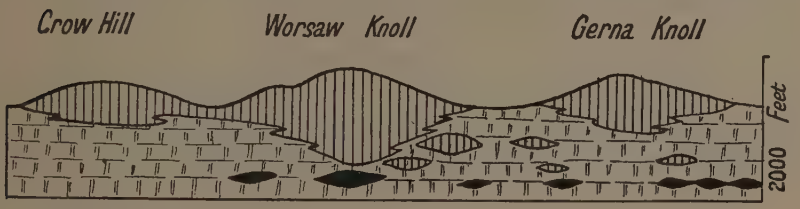


FIG. 133.—Diagrammatic Section through Reef-knolls near Clitheroe.

Solid black, Coplow Group; vertical shading, the Salt Hill Group, above which lie the Worston Shales (Pendleside Facies), not indicated. Normal limestones indicated conventionally. Horizontal and vertical scale the same. After Parkinson.

stone reef-knolls and also other similar well-known structures in the Alpine Trias, must by reason of their thickness of shallow-water deposits, have originated as local elevations on a sinking sea-floor. Subsidence is also indicated in the case of the typical oceanic coral-reef or atoll of Funafuti,[4] where a boring proved the reef to be formed entirely of coral-reef material to a depth of 1,114 feet, and in the case of the Great Barrier reef (p. 52).

The Yoredale Facies :

Rhythmic Marine Sedimentation.—In the West Riding of Yorkshire the Upper Avonian deposits are known as the *Yoredale Series*. They are essentially shallow-water deposits, as shown by lagoon-phases, limestone-conglomerates, false-bedding, and minor unconformities.[5] Unlike the usual Carboniferous Limestone, the

[1] It is advisable to record that Prof. Marr has claimed that some reef-knolls are due to tectonic causes, being on his interpretation local thickenings due to the packing together of slabs of ordinary limestone under lateral compression. The subsequent discovery of the peculiar nature of the lithological and palæontological facies appears to have invalidated this hypothesis as a general explanation (see J. E. Marr, *Q.J.G.S.*, vol. lv, 1889, pp. 327–58).

[2] See Fig. 34.

[3] See J. Johnstone, *Oceanography*, pp. 79–88. *Encyclopædia Britannica*, 11th edit., vol. vii, p. 134. W. M. Davis, *The Coral-reef Problem*.

[4] *The Atoll of Funafuti*, published by Roy. Soc., London, 1904.

[5] R. G. Hudson, *Proc. Yorks. Geol. Soc.*, vol. xx, 1923–4, p. 1.

Yoredales display an admixture of shales, and sandstones and even coals with the limestones. Changes of fauna accompany the changes of lithology. Hudson has emphasized the repetition of the rhythmic unit

limestone,
sandstone,
shale,

some ten times within the 1,200 feet of Yoredale Beds. Often the shale, which is regarded as the beginning of the unit, rests upon limestone with definite signs of a break in which the latter had been eroded into an irregular, and even pot-holed surface. The lower part of the shale is usually fossiliferous, and the upper part barren and merging upwards into the sandstone, with which a coal and a ganister or fireclay are sometimes associated. The limestone that succeeds often lies on an eroded surface, and is characterized by beginning with corals or corals and brachiopods, and ending with algæ as facies-fossils. A typical complete rhythmic unit may be stated as follows:[1]

Limestone surface, eroded and pot-holed.

Limestone:
5. Algal faunal phase or chert bed.
4. Subsidiary shale with "modified limestone" fauna.
3. Limestone with "normal limestone" fauna of corals and brachiopods or of brachiopods alone.
2. Pseudo-breccias.
1. Coral faunal phase.

Break.

Sandstone:
Sandstone or coaly shale.
Coal.
Fireclay or ganister.
False-bedded sandstone, thick and passing by alternation down into

Shale:
Unfossiliferous ferruginous shale.
Calcareous shale with "normal shale" fauna.
Limestone-conglomerate.

Break.

Limestone of preceding rhythm.

Hudson has correlated the changes in the sediments in the rhythmic unit with changes in the elevation of the continent[2] from which

[1] Hudson, *op. cit.*, p. 9.

[2] It seems unlikely that these large sedimentary rhythms had any relation to the Milankovitch climatic cycle (p. 304), though climatic changes affecting the drainage-basins of the rivers that provided the sediment, might quite conceivably have produced the same sort of variation in the supply of detritus that Hudson envisages as due to uplift and denudation. The sedimentary rhythms in the Yoredale are closely comparable with those in the Millstone Grit (p. 323).

the detritus was being derived. In his words the shale-phase "is regarded as representing the period of uplift and denudation of a once low-lying land, a land in which detrital surface-material had been accumulating in the previous limestone period. The gradual change from shale to sandstone is probably the result of the increasing gradient and greater transporting power consequent on the uplift. Such denudation must finally result in a reduction of the uplifted land-surface to its previous level. Finally, the limestone represents a period of slight or non-erosion—a period when little material was brought down, insufficient at all events to reach the Yoredale area. The major succession of shale, sandstone and limestone can thus be read in terms of uplift and denudation, reduction of land-level, and finally cessation of erosion of the land, all of which agree with the faunal sequence and minor lithological features."

Upper Carboniferous or Westphalian (sensu lato)

The Millstone Grit of the Pennine Region.

The Delta of Torrential Rivers.—As has already been pointed out, the Avonian came to an end when the sea that covered the Pennine region and gave rise to the Yoredale Beds, was invaded by the delta of a great river which drained from the northern continent (Fig. 134). The deposits of that delta are the Millstone Grit Series, which we may now examine as an example of delta-formation, taking as our guide the exhaustive investigations of Prof. Gilligan [1] and Prof. Kendall [2] in Yorkshire and Derbyshire, and of the officers of the Geological Survey in Lancashire.[3]

The most conspicuous members of the formation are the bands of coarse felspathic grit and sandstone which attain in some instances to several hundreds of feet in thickness. Peculiar blue-coloured quartz and microcline felspar are typical ingredients. The grains of quartz are rarely rounded and the felspar is unweathered. Sometimes pebbles occur of granite, pegmatite, gneiss, schist and chert. The grits are often capped by impure coals.

The grits show pronounced current-bedding, and the pebbles often occur segregated at certain levels (Fig. 50). Long ago Sorby, on the assumption that the slope of the false-bedding is an index of the local trend of the current, showed that, though variable, the general direction from which the material had been drifted was on the whole north or north-east. Later, Gilligan emphasized the

[1] A. Gilligan, *Q.J.G.S.*, vol. lxxv, 1919, published 1920, pp. 257–94.
[2] P. F. Kendall and H. E. Wroot, *Geol. of Yorkshire*, chap. xiii.
[3] W. B. Wright, R. L. Sherlock, D. A. Wray, W. Lloyd, L. H. Tonks, "The Geol. of the Rossendale Anticline," *Mem. Geol. Surv.*, 1927.

FIG. 134.—The Millstone Grit Delta.
After A. Gilligan, *Q.J.G.S.*, vol. lxxv, 1919.

A = River bringing schist from Blair Athol region.
B = River bringing porphyry from Christiania region.
c′, c″, c‴ = Rivers draining into trunk river, T, bringing granite material.
c′, c″ probably carrying sand, etc., derived from Torridonian and Old Red Sandstone.

fact that in a delta the distributaries radiate from the trunk-stream, and all streams meander; and he argues from this that a variability of direction of current-bedding is a natural feature in deltas, though in the main the directions would display a common component, as was found by Sorby to be the case in the Millstone Grit.

Less conspicuous than the grits, but really of equal importance, are the dark shales that are interbedded with them. Many of these were never true clays (kaolin being absent), but rather very fine-textured silts of quartz and felspar. This type is usually unfossiliferous and is thought by some to be freshwater in origin. But from time to time there are intercalated beds of more greasy shale with fossils that prove their marine origin. Whether freshwater or marine, the shales were clearly formed in still water and under very different conditions from the grits.

The thickness both of the individual grit bands and of the whole formation diminishes from Yorkshire [1] southwards, a feature that agrees with the evidence from the current-bedding in assigning to the formation a northerly or north-easterly derivation.

In building a delta a river deposits pebbles and sand near its mouth, and mud farther out. In the case we are considering, we find beds of grit, once sand, interstratified with beds of shale, once mud. At first sight a grit-stratum might be thought to be all of one age and younger than the shale on which it lies; but reflection will show that in reality the portion of the grit formed nearest to the old coast-line is older than the part laid down when the delta had grown out seawards. If, therefore, we assume that the Millstone Grits are the delta-deposits of a river entering the sea from the north-east, the Yorkshire part of each grit-bed would be older than the Derbyshire part of the same. Not only so, but some of the shale [2] underlying a grit in Derbyshire may well be contemporary with that same grit in Yorkshire (see Fig. 135). The pebbly layers often seen in the current-bedded grits have a similar explanation. Fig. 50 shows that the conglomerate band at the base is really composed of the larger stones that at successive stages rolled down the delta-front, and is not a separate earlier formation.

These ideas applied to the interpretation of the Millstone Grit show that:

[1] There is, however, a south-westerly thickening in South Lancashire from near Burnley towards Bolton, where the greatest known thickness is recorded. Rocks are included here below the Kinderscout Grits that form the lowest deposits to which the term Millstone Grit is applied in Yorkshire and Derbyshire.

[2] W. B. Wright, in the Rossendale memoir cited above (p. 129), shows by palæntological means that a certain marine shale found in several different areas was formed at different times, i.e. it is diachronic.

1. Each grit bed represents a vast period of time, for they can be traced for 100 miles or more;
2. Parts of the grit are contemporary with parts of the shales;
3. The grit facies must therefore transgress the time-zones, i.e. the grits are diachronous (p. 140);
4. Each grit marks a period when the level of sea and land remained more or less constant;
5. The upward change from grit to shale records either a subsidence of the sea-floor involving a transgression of the sea, or a marked diminution in the supply of coarse sediment.

FIG. 135.—Advance seawards of a Sand-delta over its own previous mud-deposits. Continuous lines bound contemporaneous deposits.

It may be seen from the character of the sediments, the occasional presence of coal, the current-bedding, the general distribution and the size of the Millstone Grit formation, that its explanation as the delta deposits of a great river, in size comparable with the Mississippi or Ganges, is supported by a variety of lines of reasoning. Assuming the correctness of this explanation we may now note some further points of interest.

Contemporary Movements.—The grits occur in groups at intervals, and each of the four groups [1] indicates a great increase in the erosive and carrying power of the river, an increase that can best be explained by a renewal of the uplifting of the northern continent. Under the influence of rejuvenation, the river built out a huge sandy delta that merged outwards into a muddy sea; but while this was proceeding, erosion was lowering the continental heights and thus lessening the river gradients, so that in general only finer material was at this later stage being carried into the area to be deposited on the top of the "grit." Earth-movement was renewed: the continent again rose and the cycle of rejuvenation and coarse sediment-deposition began once more; but the great thickness of very shallow-water deposits, both grits and muds, indicate that on the sea-ward side the delta-region was undergoing a more or less continuous slow subsidence, punctuated by more

[1] In South Lancashire there is a fifth group (Pendle Grits) below the four dealt with here. The Pendle Grits succeed the Pendleside facies of the Avonian, in which the shales resemble those of the Millstone Grit in being Goniatite-bearing.

rapid phases that are recorded by the change from grits to shales and by the presence of marine strata intercalated in the delta-deposits. These minor oscillations in the rate of subsidence of the delta are recorded in South Lancashire by repetitions of a sedimentary rhythm[1] not unlike that found in the Yoredale Beds (p. 317).[2] With but slight variations, the rhythm

coal,
grit and sandstone,
flags and sandy shale,
mudstone and shale,
marine shale, with *Goniatites*,

persists through most of the Millstone Grit and Lower Coal Measure Series. The graphic representation of the repetition of the rhythm given in Fig. 136, shows the frequency of marine phases, and how much more frequently the region approached marine conditions without actually attaining them. The diagram also demonstrates how the Lancashire region oscillated between being a

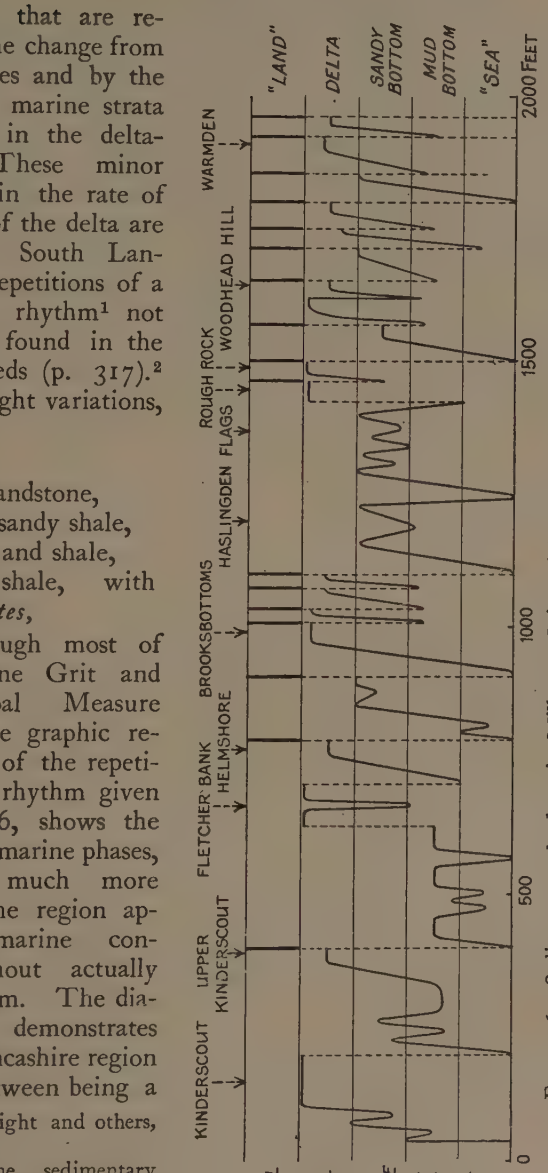


FIG. 136.—Sedimentary rhythms in Millstone Grit and Lower Coal Measures of Lancashire.
Horizontal distances, time as expressed by rock-thickness. After the Geological Survey. From the *Geology of the Rossendale Anticline*, by permission of H.M. Stationery Office.

[1] W. B. Wright and others, *op. cit.*, p. 9.

[2] The marine sedimentary rhythms of the Yoredale Beds and Millstone Grit should be compared with the lacustrine rhythm in the Old Red Sandstone (p. 303).

terrestrial delta covered with coal-swamps and an extra-deltaic shallow sea abounding in Goniatites. In some cases the lateral passage from marine to freshwater deposits in a given set of beds can be demonstrated, in other cases estuarine, freshwater and marine fossils succeed one another in a single exposure of a few feet of rock.

The original extent of the Millstone Grit Series is not capable of exact definition, but it seems probable that starting near the Scottish Border it once covered most of the north of England from sea to sea, and stretched as far south as North Staffordshire (Fig. 134). Calculations have been made by Kendall of the volume of rock that went to make up the formation, as follows:

Area once covered, at least 25,000 square miles.
Average thickness, „ „ 2,640 feet.
Original volume, „ „ 12,500 cubic miles.

On the assumption that "deposition is a measure of detrition" he estimates that, to provide the necessary material, it would require a range of mountains (assumed to be wedge-shaped and with summits 10,000 feet high) 600 miles long and 20 miles broad at their base.

The Position and Physiography of the Northern Continent (Atlantis).

The evidence for the general northerly or north-easterly derivation of the Millstone Grits has already been given, but further light is thrown on the question of the position of the northern continent by their included pebbles of granite, gneiss, etc., and by the grains of blue quartz and microcline felspar. They show that the sediments must have come from gneissic or granitic rocks; but no area of sufficient size is known to the north or north-east of Northern England where gneisses and granites of suitable types occur on the requisite scale. The Torridon Sandstone (p. 254) of the North-West Highlands, though containing a similar assemblage of materials, cannot be looked to as a source of supply; for the freshness and angularity of the particles in the Millstone Grit precludes any but a first-hand derivation from an igneous mother-formation. We are driven to the conclusion that both Millstone Grits and Torridonian drew their material from the same source, and that this lay to the north where now roll the waves of the Atlantic [1] (Figs. 132, 134).

The region drained by the great river or rivers whose delta we are studying, seems to have been subjected to a semi-arid climate,[2]

[1] It must be noted that a few of the included fragments can be matched in Scotland and Norway, but for the bulk of the material the above statements are correct (see notes on Fig. 134).

[2] Gilligan discusses, but rejects, the idea that the sediments owe their characteristics to weathering under a glacial climate.

possibly of the monsoon type with alternate dry and wet seasons; for the freshness of the felspar fragments in the grits and the absence of kaolin in the shales indicate that the land-surface was mainly broken up by insolation and temperature-changes, and not by the solvent action of surface-waters. Yet the rainfall sufficed to maintain large rivers.[1]

Little has been said about the coal seams that cap some of the grits. They show, however, that the densely forested swamps which had been restricted in the Lower Carboniferous to Scotland and the very north of England (p. 312), now spread far to the south whenever suitable conditions occurred, a fact that helps us to see in the Millstone Grit a stepping-stone from the marine Lower Carboniferous environment to the coal-swamp conditions of Coal Measure times.

Coal Measures. The Estuaries, Deltas, and Lagoons of a low Coast-land.

The Physiography of the Coal-Swamps.—It has already been pointed out that in the north of England the Coal Measures (Yorkian) succeed the Millstone Grits without any evidence of a pause in sedimentation, though with a marked change from coarse grits to fine-textured dark shales. This change implies the cutting off of the supply of coarse detritus, and the conversion of the sand-delta into a muddy one with great coastal-swamps over the whole Pennine region through which the distributaries of the Northern rivers now meandered.[2] Similar muddy swamps and coastal lowlands gave rise to coal-bearing rocks in other parts of Britain, Northern France, Belgium and Germany. The new conditions once established existed for a long while, as is shown by the immense thickness of essentially similar deposits, amounting in some coalfields to eight thousand feet of rock, all of shallow-water or even terrestrial origin. This, as has already been repeatedly emphasized, implies that the deltas underwent prolonged subsidence which in general kept pace with the accumulation of sediment (see also p. 337). Variations in the amount of subsidence are clearly shown on Plate I B.

We may now consider briefly the stratal record of this period with a view to filling in some details of the landscape just outlined.

The Coal Measures (excluding the barren Upper Coal Measures) consist almost entirely of the following rock-types: grey, black, and buff shales and fireclays, and oilshales; grey and buff sandstones

[1] Compare the mud of unweathered particles carried by the Nile to its delta.

[2] Compare the Ganges-Brahmaputra delta, which is some 250 miles wide, with at least thirty main creeks and a maze of smaller channels.

and ganisters; clay-ironstones, sometimes carbonaceous (black-band ironstones); coals, including anthracites, bituminous coals and cannel coals. Conglomerates and freshwater limestones occur very occasionally.

The *shales* are of two main types. Some are freshwater deposits, usually dark in colour owing to abundance of carbonaceous matter. These contain at times considerable masses composed of freshwater mussel shells, and also frequently display fossil plants. By increase in carbonaceous matter they pass into oilshales and impure cannels. Sometimes the shales are marine in origin: they are then greasy, light-blue rocks, known to the miners as "soapy binds." The marine origin is indicated by sparsely distributed marine fossils.

The *ironstones* are closely associated with the shales and are of the argillaceous variety known as clay-ironstones. They often occur in the shales as nodules and bands having a concretionary origin.

Shales predominate over every other kind of sediment in the Coal Measures, and by their fine texture and beautifully preserved fossil-plants show that they accumulated in shallow but very tranquil waters, probably in coastal lagoons, in and around which there was an abundance of vegetation. The marine incursions are not inconsistent with such a view, for it requires only a small subsidence to submerge low-lying coastal swamps and lagoons.

The *sandstones* are characteristically impersistent and lenticular, and are best explained as sandbanks and local delta- and flood-deposits laid down near the main river-channels. In the south-western fields a sandstone series known as the Pennant Sandstone attains a great thickness between an upper and a lower group of normal coal measures. It clearly records a larger and more persistent sand-delta than is known from any other coalfield.

The *coals*, though only forming a very small fraction of the Coal Measures, impart a peculiar interest to these rocks. Despite a great amount of research, there still remain many unsolved problems in connection with their formation. From the point of view of the physiographical environment in which they originated, Carboniferous coals seem to fall into two classes: [1]

[1] For discussions of the nature and origin of coals and cannels, etc., see D. White and R. Thiessen, *Bureau of Mines, U.S.A., Bull.* 38, 1913; R. Thiessen, *ibid., Bull.* 117, 1920, and *U.S. Geol. Surv. Professional Paper*, No. 132, 1925, pp. 121–35; M. C. Stopes and R. V. Wheeler, *Monograph on the Constitution of Coal, Dept. Industrial and Sci. Research*, London, 1918; D. White in W. H. Twenhofen, *A Treatise on Sedimentation*, London, 1926, pp. 266–316; G. Hickling, *Trans. Inst. Mining Eng.*, vol. liii, 1916–17, pp. 137–52; Fischer and Schrader, in *Fuel*, 1922. H. Potonié, *Entstehung der Steinkohle*, 6th edit., revised by W. Gothan, 1920. R. Potonié, *Einfuhrung in die allgemeine Kohlenpetrographie*, Berlin, 1924.

(*a*) *Humic coal*, mostly formed *in place* as peat, from dead swamp- and terrestrial vegetation.[1]

(*b*) *Cannel coal*,[2] formed in stagnant water from decomposed debris, partly of aquatic plants, but mainly of wind-blown spore-cases, and drifted swamp-vegetation.

(*a*) **The humic coals** are the ordinary house, coking, and steam coals, semi-anthracites and anthracites, the two latter being distinguished by possessing a higher content of fixed carbon and less of the volatile hydro-carbons. All these varieties are united in the humic class, because, as the term implies, they were formed from "humic debris," [3] that is to say from the various different plant-organs belonging to all sorts of vegetation, which had severally undergone decay to varying degrees before and during their entombment in the Carboniferous peats. In general the organs with soft cellulose-tissues were usually completely destroyed; but wood, bark, and cuticular skins of leaves, stems, spores and seeds together with any resins that may have been scattered through the tissues, though altered to varying degrees, still retained a portion of their original plant-structure.

The plants that gave rise to this class of coals were terrestrial ones that grew chiefly in swamps; and when dead, their parts accumulated as peat [4] on the spot where they had lived; for with rare exceptions the coals are found to overlie either fireclay or ganister, both of which by their freedom from lime and alkalies, and by their unlaminated texture reveal themselves as the soil on which the vegetation grew. Often these so-called "seat-earths" and "underclays" are full of rootlets.

Peat-formation on a large scale is only possible when the plant-debris is either slightly submerged or saturated with water which prevents the rapid and complete destruction of the tissues (passing into water, carbon-dioxide and marsh-gas), that otherwise results from fungus and bacterial fermentation.[5]

The Coal Measure peats were not like the moorland- and fen-

[1] Some humic coals may represent vegetation drifted out beyond the mouths of rivers, and prevented by reason of its buoyancy from settling on the sea-floor until it had passed beyond the limits of detrital sedimentation. For the Drift Theory, see E. C. Jeffrey, "Origin and Organization of Coal," *Mem. Amer. Acad. Arts and Sci.*, vol. xv, 1924, pp. 1–39.

[2] Torbanites and bogheads are cannel-like rocks, but are perhaps best regarded as a third class of coal (p. 332). (See Thiessen, *op. cit.*, 1925.)

[3] Stopes and Wheeler, *op. cit.*, 1918, p. 19.

[4] For the origin and formation of peat, see D. White, *Bureau of Mines, U.S.A., Bull.* 38, 1913, pp. 165–86; R. Thiessen, *ibid., Bull.* 117, 1920, pp. 13–22.

[5] Within the peat itself anaerobic bacteria are the most important agents of destruction, while stagnant conditions and the presence of toxins are the principal hindrances to destruction.

peats that are forming at present in Britain; but we can draw a close comparison with others which are accumulating in thickly forested swamps in different parts of the world (p. 335). In such peats, stems, branches, and roots of trees make up an important part of the whole, to which the other organs of the plants add their contribution chiefly in the form of cuticle or outer skin-substance. As the peat becomes buried and compressed below new additions of dead vegetation, it becomes a soft brown substance that cuts like butter, irrespective of the nature of the plant-parts of which it is made, whether they be macerated fragile leaves or hard wood; but, if the bulk of the water is dried out of this material, it can be seen to consist of tree-trunks, chips of wood and bark, and fragments of stems, leaves, fruits, etc., the smaller and softer parts of the plants being often reduced to a mass of disintegrated cell-walls and fibres. The cuticle forming the skins of spores, pollen-grains, leaves and stems, is far less susceptible to decay than the cellulose and ligno-cellulose that are the main constituents of the other parts of plants; and therefore, despite the small volume of skin compared with the rest of the plant, cuticle always forms an appreciable element in the peat.

The buttery peat-substance is a colloid in the condition of a hydrogel, and as such, if dried under pressure, tends to become a hard solid mass having properties akin to those of coal. The material of the hydrogel, though derived partly from cellulose but mainly from ligno-cellulose, is now an ulmin quite different chemically from those substances.

Though Coal Measure plants differed considerably in their organization from modern ones, their tissues were without doubt made of the same substances, and were therefore liable to the same changes as those of the plants of to-day. The microscopic study of coals has made it clear that they have passed through a stage when they were peats resembling to a remarkable degree the forest-peats just described.

Most coals consist of alternating layers or rather lenses of bright and dull coal with, at frequent intervals, partings of a charcoal-like material (*fusain*) that blackens one's fingers. Fusain has distinctive chemical and physical characteristics that have long been recognized. More recently Dr. Marie Stopes [1] has claimed the existence of three other constituents to which she applied the names *vitrain*, *clarain*, and *durain*. According to her, bright coal is made up of clarain and vitrain; dull coal of durain and fusain. Vitrain appears to be a solidified hydrogel exhibiting an almost homogeneous structure: clarain on the other hand to be a mixture of various macerated,

[1] M. C. Stopes, *Proc. Roy. Soc.*, ser. B, vol. xc, 1919, pp. 470–86.

but often still recognizable plant-tissues lying in and impregnated by a vitrain-like material. In durain this latter is deficient, and the cuticles of leaves and spores predominate. Though the recognition of such substances may contribute to an understanding of the constitution of coal, direct microscopic examination of thin sections has perhaps thrown the greatest light on the nature of the Coal Measure peat-swamps. The work of many observers seems to have now proved the bright parts to represent, in the main, pieces of the wood and bark of trees, usually greatly flattened, but occa-

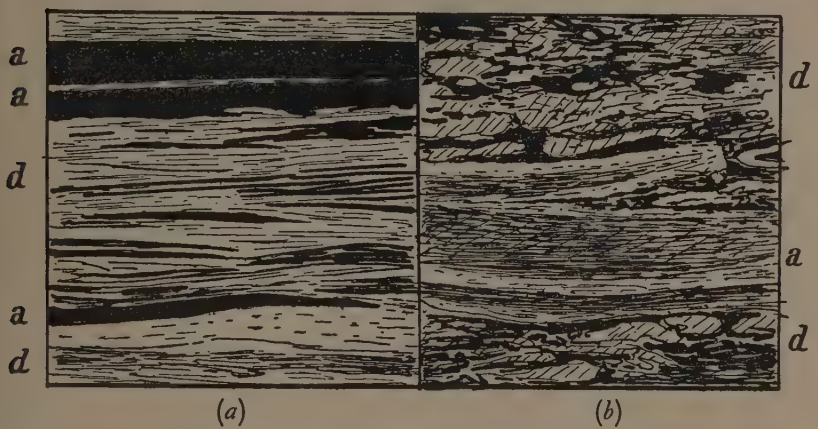


FIG. 137.—Vertical Sections of Bituminous Coal.

(*a*) Polished vertical opaque section of about $\frac{1}{3}$ of an inch of dull coal, showing it to be laminated, the dark streaks being anthraxylon (*a*), and the rest detritus (*d*). × 6.

(*b*) Transparent vertical section of about $\frac{1}{6\frac{1}{3}}$ inch of the detrital part of (*a*) showing it to be chips of anthraxylon (*a*) with indications of structure (sometimes perfectly preserved) and vegetable debris, spore exines, etc., in a matrix (black) of excessively macerated material. Note the vegetable debris is here light. × 130. Both sections after Thiessen's photographs.

sionally almost uncrushed. Consisting chiefly of wood, the bright laminæ are sometimes termed *lignitoid* or *anthraxylon*[1] (Fig. 137 *a* and *b*). The dull coal on the other hand is itself finely laminated (Fig. 137 *b*). Some of the laminæ are bright coal, representing small bits of anthraxylon; others are dull and consist of masses of flattened spore-cases and leaf-cuticles, or of an almost structureless substance derived from rotted and macerated vegetation.[2] Scat-

[1] R. Thiessen, *op. cit.*

[2] Thiessen (*Bull.* 38, *cit.*, p. 279) states that two derivatives, one from cellulose and the other from cutin, are observable in the almost structureless matrix lying between the larger recognizable plant organs in the coals. The second is particularly abundant in cannels and was derived from spores. Presumably he uses the term "cellulose" to include ligno-cellulose.

tered through the dull coal are small bodies that have a resinous nature, and certain inorganic material such as iron-pyrites, etc.

The direct vegetable origin of nearly every part of the coal can therefore be demonstrated under the microscope. It must, however, be understood that the woody structures seen in coal retain in an unaltered state none of the organic compounds of which they originally consisted. As in modern peats, so in the Carboniferous ones, new ulmic compounds derived by bio-chemical reactions from cellulose and ligno-cellulose, and perhaps also partly from cuticle, took the place of the original substances, yet preserved the cellular structure of the plant-organs, in so far as these had escaped complete destruction. The cuticular parts of the plants were, however, more resistant to the bio-chemical attack, and consequently remained perhaps completely unaltered in the peat-stage, and even now are barely changed.

The changes just described took place in the peat-swamps; but the subsequent conversion of the peat into coals and anthracites [1] has been effected by physical and chemical changes that have been governed mainly by tectonic factors. In the conversion, the dynamo-chemical reactions have therefore had a variety of material to deal with. In general the different plant-substances preserve the original cell-structures in the following order of perfection:

Cellulose .	Badly—usually completely macerated to bits of cell-walls.
Ligno-cellulose.	Fairly well, but the cells usually collapsed and crushed and parts of the wood often replaced by amorphous material (? vitrain).
Cuticular. .	Very well—cells sometimes almost uncrushed; cell-walls now translucent.
Resin . .	Very well—often retains the shape of the cell it originally filled.

It will now be clear that the properties of any particular coal must depend partly on inorganic ingredients, such as clay, iron pyrites, calcite, etc.; partly on the nature of the plant-organs, whether leaves, roots, stems, spores, etc.; partly on the type of plant; partly on the degree to which bio-chemical decomposition and change had taken place during the formation of the peat; and partly on the subsequent tectonic and chemical phenomena to which the peat has been subjected.

[1] The microscope shows that anthracites are made up of plant-debris similar to that of the other humic coals (H. G. Turner and H. R. Randall, *Jour. Geol.*, 1923, vol. xxxi, p. 306. A. Stuart, *Geol. Mag.*, vol. lxi, 1924, p. 360. C. A. Seyler, *Fuel*, vol. ii, 1923, p. 217). J. Roberts, "The Origin of Anthracites," *Proc. S. Wales Inst. Eng.*, vol. xl, 1924, pp. 97–138.

(*b*) **The Cannel Coals** occur in local lenticular seams usually a few inches and rarely more than two feet in thickness. They are dull earthy-looking fuels often with a high ash-content. As a result of possessing a higher proportion of hydrogen and oxygen relative to carbon than do the humic coals, they burn with a smoky flame; and before the days of incandescent mantles were highly valued as gas coals. Less brittle also than ordinary coals, they break with a subconchoidal fracture and present a general amorphous appearance, but under the microscope they are seen to consist largely of the crushed skins or exines of spores (Fig. 138 *a*). The bulk

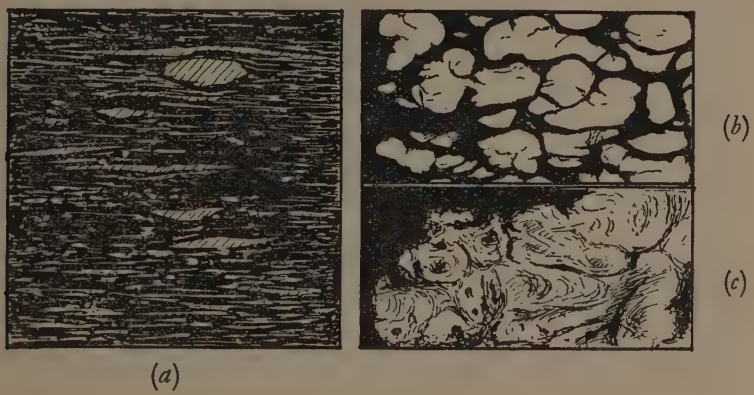


FIG. 138.

(*a*) Thin transparent section of Cannel. A laminated felt of spore-exines and cuticle (longer strips) with a large granule of resin towards the top. × 150.

(*b*) Torbanite, Torbane Hill. Shows numerous "yellow bodies" set in an amorphous dark matrix. × 100.

(*c*) Part of a "yellow body." The structures shown have been held to prove the yellow bodies to be thalli of a colonial alga, *Pila scotia*, Renault. × 1000. All three figures after Thiessen's photographs.

of the flora of those times reproduced [1] itself by spores; and on account of their transparency the exines are usually the most conspicuous objects in microscopic preparations of both coals and cannels, and in the latter are often the only recognizable plant-remains, there being frequently no sign of wood, bark, leaves, etc. This has given rise to the view that cannel was essentially formed of spores, and it is therefore sometimes termed *spore-coal*. There is

[1] Microspores and megaspores were produced in such large quantities to insure wind-fertilization, that at times the forests and even the surfaces of the pools must have been deeply carpeted with their yellow dust. The heterosporous method of reproduction demands abundant moisture for fertilization, and its prevalence in the Coal Measure plants denotes a moist climate and swampy environment.

probably always, however, a certain proportion of amorphous matrix which has been regarded by some as having originally resembled the modern *sapropel* or vegetable-pulp which is known to form on the bottoms of stagnant lakes and lagoons as the result of the complete fungoid and bacterial decomposition of the microscopic plankton, algæ, and larger aquatic vegetation together with some admixture of terrestrial plant-debris. Cannels have on this assumption sometimes been spoken of as sapropelic coals; but this classification has now been generally given up, because cannel does not appear to have originated mainly from aquatic vegetation, and because its structureless matrix is not essentially different from the amorphous matrix in humic coals (p. 329). At the present time the generally accepted view is that cannels have originated, not as peats, but as aqueous deposits formed in pools, backwaters, and bayoux, from stems and leaves that had fallen in from the banks, and from spores blown in from the neighbouring forest. An essential feature of the concept is the general destruction of the bulk of the lignocellulose and cellulose [1] of the plants, and the preservation of the cuticular and resinous portions, more particularly the cuticular spore-exines. It is their abundance, no doubt, that imparts to cannel its distinctive chemical characteristics noted above. The proportion of amorphous material to recognizable plant-organs was determined by local factors, such as currents and oxygen-content in the water, type of vegetation, etc.; and is naturally found to vary considerably in different cannels. Their relatively high mineral content, their occurrence in local lenticles, and the not-infrequent preservation of fossil-fish and amphibia in them, are all characteristics that might be expected in sediments originating in this way.

In most cannels there are scattered through the matrix a few small globular yellow bodies about which considerable discussion has taken place (Fig. 138 *b* and *c*). In **torbanites** (**bogheads**), which otherwise resemble cannel, these form a conspicuous proportion of the whole rock, the rest being usually poorer in spores and richer in the almost structureless matrix than are ordinary cannels. These yellow bodies have been claimed to be the thalli of colonial algæ, for which reason torbanites have sometimes been termed *algal coals*.[2] Thiessen is the most recent worker to maintain this view in an elaborate memoir [3] in which he demonstrates the great similarity in the structure of the yellow bodies to a South Australian alga, *Elaeophyton*, which is said to secrete oil. At certain seasons

[1] See p. 330.

[2] H. Potonié, *Abhandl. preuss. geol. Landesanstalt.*, Bd. 48, 1906, and *Die Entstehung der Steinkohle*, 5th edit., 1910.

[3] R. Thiessen, *U.S. Geol. Surv. Professional Paper*, No. 132, 1925, pp. 121–135.

this supposed plant forms a scum on the surface of the Coorong or lagoon at the mouth of the Murray River, and is blown to the shores by the wind. There it forms a black rubber-like deposit known as *Coorongite*. A similar substance *N'hangellite*, also supposed to be of algal origin, occurs on Lake N'hangella in Portuguese East Africa.[1] Coorongite consists of masses of cellular material which closely resemble the yellow bodies in torbanites.

The algal interpretation of the origin of torbanites has been frequently challenged, one of the most cogent objections being the comparatively uncompressed nature of the bodies, which certainly have the appearance of having grown after the consolidation of the rock. R. Potonié, son of the author of the algal theory, has recently shown in conjunction with Hellmers that melted paraffin shaken violently in an aqueous solution of gelatine almost to the point of solidification and then allowed to cool, gives rise by coagulation to aggregates of paraffin displaying a structure completely comparable with that of the yellow bodies in torbanites.[2]

It is therefore clear that much more work remains to be done before the torbanites shall give an unequivocal answer to the question as to how they originated.

Cannels pass by addition of inorganic detritus into carbonaceous shales; but the latter have to be distinguished from **oil-shales** in which the inorganic sediment seems to have been impregnated by a carbonaceous substance that was perhaps originally akin to a sapropel (p. 332). Oil-shales on distillation yield paraffins and olefines, and a residue of laminated ash, whereas cannels and humic coals give hydrocarbons of the benzene group and a residue of coke. There are also chemical and physical characteristics that suggest that the carbonaceous part of an oil-shale originated through a chain of reactions quite different from that involved in coal- and cannel-formation, and that the original organic matter may have been derived partly from plants and partly from animals.

Having briefly considered what light the constitution of the two great classes of coals throws on the general environment in which each accumulated, we may now enquire what further information they give about the **Ecology** of the great swampy deltas of the English Coal Measures.

The coastal-swamps and lagoons in which they formed were very nearly at sea-level, as is shown by the occasional marine bands that are associated with them; but it is improbable that the plants grew in salt water, as do the mangroves and other plants of the present-day mangrove-forests which fringe tidal estuaries, overrun

[1] L. A. Boodle, *Roy. Bot. Gardens, Kew, Bull.* 5, 1907, pp. 145–51.
[2] R. Potonié and H. Helmers, *Kohle u. Erz*, 1926, pp. 1057–62.

salt-marshes and line muddy coasts in the tropics. With hardly an exception, the modern representatives of the common Coal Measure plant-classes eschew marine habitats, though they show a decided predilection for moist and swampy freshwater ones, as did their Carboniferous ancestors, many of which exhibit in their organs the characteristics of semi-aquatic plants.[1] We must conclude that the salt water was kept out of the swamps by low coastal-bars and the dense vegetation itself, while the latter in the neighbourhood of the streams also filtered off the river detritus, for the coals are remarkably free from this.

The very formation of peat implies a water-logged condition of the vegetable debris, because the aseptic surroundings necessary for the preservation of any part of the plants could only have been brought about beneath stagnant and unoxygenated water. Most coals contain frequent bands of fusain (p. 328), the charred appearance of which, and the fact that it contains more carbon than other coal, gave rise to the idea that it represents the product of forest fires; but this view is untenable. All the features of fusain can be better explained on the assumption that the plant-debris underwent a more rapid aerial decay at or near the water-surface of the swamp than did the more completely submerged portion that has become bright coal.

The lamination of coal into dull and bright layers has been thought by some to be due to seasonal and other changes in the water-level in the swamp, that controlled the rate of bio-chemical change in the surface peats; but recent microscopic work seems to discredit this explanation and to show, as already pointed out, that the bright and dull layers represent rather the differences in the nature of the plant-organs that originated the coal.

Lomax [2] has claimed that the different layers in a coal may also record a variation in the vegetation during the accumulation of the seam. In two examples described by him, the first plants to establish themselves on the mud-flat or sand-bank (now the seat-earth) were small delicate forms, like ferns or mares-tails (*Calamites*). Their remains provided the necessary soil for conifer-like trees, known as *Cordaites*, together with the giant club-moss trees, *Lepidodendron*. Large trees (*Bothrodendron and Sigillaria*) next took possession, as is indicated by the enormous quantities of their spores in the succeeding layers. Finally in the uppermost part of the seam a return to the earliest condition is recorded by a repetition of layers predominantly consisting of ferns, calamites, and lepidodendrons.

[1] See especially White in Twenhofen, *op. cit.*, p. 271.

[2] J. Lomax, *Trans. Inst. Mining Engineers*, vol. i, 1915–1916, pp. 127–31 and 137–57, espec. pp. 127–8 and 148–50.

In a discussion of the modern equivalent of the coal-forming environment, David White[1] has written as follows: "In no part of the world to-day are the genetic conditions of the great ancient coal formations to be found except locally and on a relatively small scale. Topographically, climatically, and botanically their nearest semblance is to be found in the coastal and near-tide-level swamps of the South Atlantic and Gulf States [of U.S.A.], the great estuarine and lowland swamps of India, and the lagoons and swamps of the Indo-Pacific zone of heavy rainfall." Shaler's description of the Dismal Swamp of Virginia and North Carolina gives a good idea of the environment in the first of these groups.[2] Here, before draining was undertaken, there was an area some 40 × 25 miles, nearly at sea-level, covered by densely-forested peat-swamps with a large lake near the centre. The trees showed special adaptations for a life in almost permanently waterlogged peaty soil, itself the product of dead vegetation, and covered with fallen logs. This part of the swamp reproduces in general the environment under which humic coal is thought to have accumulated; while the conditions in the stagnant forest-girt lake may be regarded as analogous to the environment requisite for cannel formation. The climate, however, of the Dismal Swamp includes at times very cold seasons, a factor to which the plants of the Coal Measures do not seem to have been subjected.

Koorders and Potonié have shown that in almost every aspect save that of size and proximity to the sea, the inland swamp of Eastern Sumatra[3] which lies in the equatorial rainbelt, reproduces the environment of the Carboniferous coal-swamps. In the Sumatran swamp the peat is up to 30 feet thick and covered with tea-coloured, stagnant, fresh water to a depth of 2 feet. In this grows a dense forest of trees with special adaptations to the peculiar habitat. The destruction of dead vegetation is so rapid and complete in the hot moist climate of Sumatra that the accumulation of peat is only possible as a result of the almost incredible rate of plant growth (a ten-year-old tree may be 100 feet high) combined with the permanent water-cover. The temperature found in Sumatra may well exceed that which prevailed during the Coal Measures, though a study of the fossil plants makes it clear that the latter originated in a hot moist climate.[4]

[1] D. White and R. Thiessen, *op. cit.*, 1913, p. 67.

[2] N. S. Shaler, *10th Annual Rep. U.S. Geol. Surv.*, pt. 1, 1890, pp. 255–339.

[3] H. Potonié, "Ein von der Hollandish-Indischen-Sumatra Expedition endecktes Tropen-moor," *Naturwiss. Wochenschr.*, Jena, 1907, pp. 657–66; and *Die Entstehung der Steinkohle*, 5th edit., 1910, pp. 153–4.

[4] According to Köppen and Wegener the principal coal deposits of all ages originated in what was the equatorial belt at the time of their formation (see W. Köppen and A. Wegener, *Das Klima der geolog. Vorzeit*, 1924, p. 8).

The following are the chief botanical evidences for the last statement: the large size and thin walls of the cells in many of the plant-tissues; the large size and often much dissected, drooping, fern-like fronds; the smoothness of the bark; the absence of seasonal growth-rings; the prevalence of heterospory (see note on p. 331); devices for seed-flotation; and the development of subaerial roots. All of these characteristics indicate a perennial and abundant rainfall, which is also necessary to maintain the swamp-environment that alone can save the dead vegetation from becoming water, carbon-dioxide and marsh gas.

Alluvial Phenomena of the Coal Measure Swamps and Deltas.

The great reduction in volume involved in the conversion of peat to coal has already been commented on (p. 314). This is mainly the result of dynamo chemical changes subsequent to the peat formation; but it may be further remarked that one foot of peat itself represents perhaps 12 feet of uncompressed vegetable debris, the reduction here being chiefly due to biochemical changes.

The recognition of the great shrinkage undergone in these processes helps us to explain some curious phenomena that throw light on the environment in which the coal seams originated. Sometimes a seam of coal appears to split, and to develop between its top and bottom a mass of sandstone that arches up the upper part of the coal (Fig. 139). This arrangement is best explained by assuming that the peat-accumulation went on up to a point when it was interrupted by the local deposition of a sandbank across the swamp, perhaps by a flood or owing to the shifting of a river channel. Later the peat, the accumulation of which was elsewhere uninterrupted, spread across the sand; so that, in effect, the bed of peat lying below the sand was separated from that lying on it, by the thickness, say 12 feet, of sand in the channel, and elsewhere by the same thickness of peat. The 12 feet of sand during its consolidation to sandstone has retained practically its original thickness, whereas the 12 feet of peat has been reduced to, say, 6 or 8 inches of coal. By this reduction, the upper peat-layer (now coal) has, as it were, been lowered bodily downwards except where the sandstone occurs; hence the arching of the upper part of the coal seam over the sandstone lens.[1]

We have already referred to the supposed origin of cannel in lakes and pools from the indestructable parts of macerated vegetation. Where a coal contains a local seam of cannel it is usually thicker than elsewhere. In explanation Kendall points out that "cannel, having presumably undergone most of its chemical changes during deposition

[1] For other sections illustrating this, see Kendall and Wroot, *Geology of Yorkshire*, p. 144.

acts as a material relatively incompressible, and whenever a pool of vegetable mud took the place of an equal thickness of peat-stuff in the original deposit, the spot is marked in the coal seam by a swelling mass of cannel much thicker than the bright coal." [1]

The deterioration of coals by the introduction of detrital matter records the flooding of the peat-morasses by the streams that meandered across the delta. There are also many places where locally a seam has been completely destroyed, and its place taken by sandstones and shales. Such "wash-outs" record a sudden change in the course of one of the streams, a frequent phenomenon on flood-plains and deltas of present-day rivers when in flood.

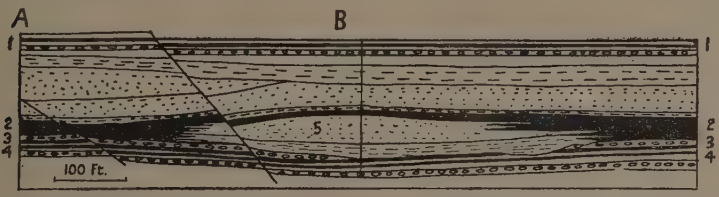


FIG. 139.—The splitting of the S. Staffordshire Thick Coal at Baremore Colliery. The figure shows towards the sides, the splitting of the seam, and in the centre the wash-out of the whole of the lower part of the seam and of the underlying strata down to below the Upper Heathen Coal.

1, Brooch Coal. 2, Thick Coal. 3, Upper Heathen Coal. 4, Lower Heathen Coal. A and B, Shafts. After Beete-Jukes.

The splitting and local disappearance of a coal seam results in some cases from other causes than those just described. In the first place slight earth-movements in the area of accumulation may have had this effect. We may instance the splitting of the Ten Yard or Thick Coal of the Dudley district of South Staffordshire northwards [2] into the fourteen seams recognized in the Cannock district of the same coalfield, with an aggregate of 250 to 300 or even 400 feet of sandstones and shales between them (Fig. 140 *b*, which only covers part of the area, the seam having split into 7 coals only). This can be explained if we assume that in the south near Dudley, subsidence just kept pace with the deposition of the great mass of peat, whereas the district to the north sank intermittently, the vegetation being at times killed off by the too great depth of water and its place being taken by mud-flats, until eventually a new swamp-growth could be established on them by the extension outwards of the vegetation which persisted

[1] *Op. cit.*, p. 149.

[2] Southwards the Thick Coal rapidly deteriorates owing to inclusion of detrital matter, and ends off against an old ridge (Lickey Hills) that stood up above the swamp-level and was therefore not buried under peat.

throughout on the southern edge of the submerged region (Fig. 140 *a*).

In some cases the deterioration and disappearance of a seam must similarly be attributed to differential movement. Thus the Barnsley and Silkstone seams deteriorate near Wakefield. Green attributed this to elevation, but Kendall has shown reasons for believing that it was due to subsidence and to sedimentation in excess of peat-formation. As he puts it, "the seam . . . did not die a dry death, but was drowned" (*op. cit.*, p. 152). This appears to have been the usual cause of the upward termination of coal seams; for they

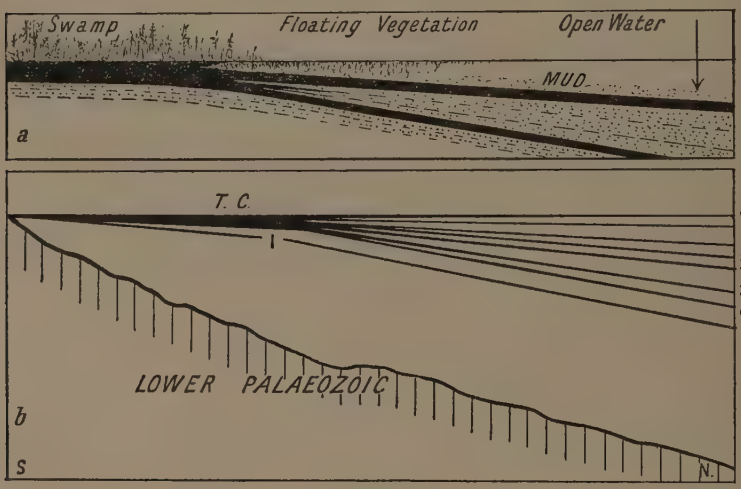


FIG. 140.

(*a*) The effects of differential sinking of a coal-swamp. On the left, slow subsidence and continuous peat-growth; towards the right more rapid intermittent subsidence with interruption of peat-growth by deposition of mud.

(*b*) Diagrammatic section to show the splitting northwards of the Thick Coal of S. Staffordshire from its southern termination against the Lickey ridge. 1, Heathen Coal. T.C., Thick Coal. 2–8, Its equivalent in the north, separated by a collective thickness of about 350 feet of measures. Based on Lapworth.

generally pass upwards without any break into shales which in some cases enclose the upright butts of the trees that were growing on the peat.

Some of the seams (to which reference will be made later) cover enormous areas, but many are more or less local. In some cases the seam ends where the vegetation on the outer edges of the swamps diminished as the deeper waters of lagoons and lakes prevented its growth. In other cases the peat dwindled away as slight elevations were approached on which the plant debris lay above the level of per-

manent saturation by water In such circumstances, as already pointed out, peat-formation on a large scale is impossible. Yet other seams end where the rivers by their flood-deposits introduced abundant detritus or by their erosion washed away the peats.

Kendall has thrown a new light on the physiography of the Coal Measure deltas by showing that the rocks contain evidence of contemporaneous earthquakes,[1] which, it is well known, produce particularly striking effects in the unconsolidated formations of modern alluvial tracts. The sliding and lurching of muds, quicksands and peats, the forcing of quicksands into peats and muds, the ejection of water and sand at the surface as "sand-blows," and the local subsidences that produce shallow lakes on the present-day deltas, estuaries, and flood-plains, can be seen recorded in the peculiar sedimentary structures of the Coal Measures, many of which are illustrated in his writings.

Our comparison of the Carboniferous swamps with those of to day fails in one respect; namely size. The extent of individual peat-swamps in Coal Measure times as indicated by the coal seams was often amazingly large. It is clear that at this epoch many parts of the world had been reduced by prolonged denudation and sedimentation to vast plains lying barely above the level of the sea. At the present time the earth has not sufficiently recovered from the Alpine orogeny for similar conditions to be found anywhere. Two examples to illustrate the enormous size of the Carboniferous swamps may be cited. The famous Pittsburg Coal in the United States originally covered some 22,000 square miles (three times the size of Wales), and is even now known to exist in a workable state (6–10 feet thick) over 6,000 square miles. The largest of the North American swamps of to-day is the Dismal Swamp with an area of about 1,000 square miles. Less extensive than the Pittsburg Coal, but particularly interesting as a British example is the thin coal variously known as the Halifax Hard Bed or Ganister Coal of Yorkshire, the Alton Coal of Nottinghamshire, the Crabtree Coal of North Staffordshire, and the Upper Foot, Bullion or Lower Mountain Mine of Lancashire; for its roof, consisting invariably of marine shale with characteristic fossils, serves to identify it and to prove it to have originated everywhere at sea-level. It extends from Leeds to Nottingham, through North Staffordshire and Lancashire, and possibly into Flint, over an area of perhaps 5,000 or 6,000 square miles. Practically everywhere it rests on a seat-earth full of rootlets and it was obviously the peat

[1] P. F. Kendall, *Proc. Geol. Soc.*, Jan. 17, 1919, and Pres. Address, Sect. C, Brit. Assoc., 1922, *Rep. Brit. Assoc.*, 1922. P. F. Kendall and H. E. Wroot, *op. cit.*, pp. 151–161. M. Fuller, "New Madrid Earthquake," *Bull.* 494 *U.S. Geol. Surv.*, 1912.

accumulation of one vast coastal-swamp that came to an end by being invaded by the sea.

It seems probable from this and similar evidence that the whole of England north of Warwickshire, and possibly a portion of the North Sea basin was in Coal Measure times part of a single delta, everywhere nearly at sea-level. The size is not outstanding for the whole of England could be placed within the area covered by the delta and alluvial plains of the Lower Mississippi valley. As already suggested, another delta or deltas were in existence in South Wales and in Southern England.

All these great expanses were covered with forest and swamp in which the dominant plants were Lycopods, Equisetales, and seed-ferns (Pteridosperms) with Cordaites and primitive Conifers in less abundance. In the muddy waters of the streams and pools mussels abounded, and fish of various sizes up to the ten-foot giants, *Rhizodus* and *Megalichthys*, disported themselves. Amphibians were rarer In the forests there was a variety of insects, such as dragon-flies and cockroaches; and many sorts of Arachnids, spiders, spider-like forms, and scorpions. Under these surroundings were slowly built up the fuels which have been the basis of British industry during the last two centuries, and have at the same time made black the face of so much of "England's green and pleasant land."

Upper Coal Measures. The Oncoming of Semi-arid Conditions and the Dawn of the Altaid Orogeny.

Where the uppermost portion of the Productive Coal Measures is preserved from erosion, as it is in many parts of the Midlands, it is usually followed conformably by a variable but often great thickness of barren Upper Coal Measures. These rocks have been dealt with in Chapter VII, where it has been shown that they are predominantly red in colour, though there is towards the middle of the sequence a grey series containing inferior coals which appears to record a repetition of the coal-swamp environment. The red measures clearly denote an origin under semi-arid desert conditions.

In the South Wales, Bristol and Radstock coalfields the rocks that are contemporary with the Midland barren red measures are mostly grey, and contain normal Coal Measure rock-types. Evidence will now be given to show that there were great earth-movements in progress; but the nature of the geographical changes brought about by them is not known with certainty. The Upper Coal Measures usually follow conformably on the Productive Series, but there is one belt of country in which there is a strong unconformity between the two (Plate I B). This belt runs from the Forest of Dean, through the Malvern and Abberley Hills and Wyre Forest into

Coalbrookdale in Shropshire. The same relationship of the two series is also observed locally near Oswestry and Flint. Throughout this region, and especially in the Malvern and Abberley districts, the Productive Measures were strongly folded and deformed mainly along north to south axes by mountain-building movements which are sometimes termed the *Malvernian movements*. Great ranges came into being, and were eroded away before that region again became the site of sedimentation in Upper Coal Measure times. This mountain-building is particularly interesting as being the first phase recorded in this country of the great Altaid orogeny that so profoundly affected the world in late Carboniferous and Permian times.

We find ourselves here at the point in geological history at which we began our studies. In Chapter VI a brief outline was given of the effect produced by the Altaid movements in Western Europe, and it is not proposed to supplement that account, because the descriptions that have been given of the Alpine and Caledonian orogenies have introduced the reader to the tectonic processes involved in the building of folded mountain-chains. At the same time he will do well to bear in mind that it was the great geographical revolution induced by these movements that brought the Palæozoic era to its close, and ushered in all the changes of land and sea, climate, plants and animals that mark the oncoming of Mesozoic times. The brief treatment accorded here to the Altaid orogeny must therefore not be taken as implying that it was of less importance than the other orogenies dealt with. In many respects the reverse is the case, for as far as Britain is concerned, it was the Altaid movements that controlled directly or indirectly the geological structure of practically all England, South Wales, and much of Ireland.

IX. VOLCANIC PROCESSES

CHAPTER XXV

In describing the geographical environment of the different geological periods, reference has repeatedly been made to contemporary volcanic activity and the relation of that activity to the earth-movements. In this final chapter some of the volcanic processes that are best illustrated in the British volcanic rocks will be dealt with; but here, as elsewhere in this book, we shall in general adopt a stratigraphical arrangement.

Pre-Carboniferous Systems.

In Pre-Carboniferous times the principal volcanic episodes, those of the Pre-Cambrian, Ordovician and Devonian (p. 366), are recorded chiefly by the lavas and ashes poured out at the surface and by subterranean reservoirs and intrusions; but owing to the destruction and dislocation of the rocks it is rarely possible to study the vents in detail. Some were subaerial, others submarine; and probably every type of volcano known to-day contributed to the great igneous piles of these three systems.

We shall, however, only draw upon them for an illustration of deep-sea, submarine volcanoes. Such volcanoes have left their record in the spilitic "*pillow lavas*" that are so commonly found associated with the geosynclinal sediments of the Ordovician (p. 268) in many parts of Britain, and which also occur in the Devonian of South-West England. A pillow-lava consists of an accumulation of vesicular masses which have been variously compared to bolsters, sacks, pillows, etc. (Fig. 141). The pillows as a rule vary in diameter from $1\frac{1}{2}$ to 3 feet, but may attain 8 feet. Each is bounded by a skin of chilled rock, and often shows within itself a concentric arrangement of vesicles. These structures seem to indicate that the lava was poured out below a sufficient depth of water to prevent explosions, and that its surface was quickly frozen over, and much steam and gas imprisoned in vesicles; but the continued flow of fresh material rolled forward the partly consolidated and skinned-over lava, and piled it on itself in the pillow-like arrangement.[1]

[1] See Tempest Anderson, *Q.J.G.S.*, vol. lxvi, 1910, p. 631. H. Dewey and C. Reid, *Q.J.G.S.*, vol. lxiv, 1908, pp. 264–72. Tyrrell, *Principles of Petrology*, p. 38.

The association of pillow-lavas with radiolarian cherts and fine-grained shales has been commented on (p. 268), and conforms with the idea that such lavas have usually been the outpourings of volcanoes situated below geosynclinal seas (see pp. 16, 269, 309).

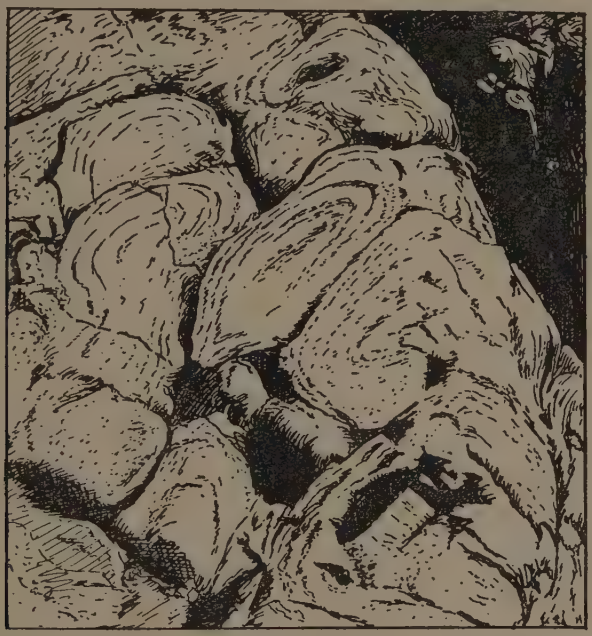


FIG. 141.—Pillow lava in the Dalradian Series. Tayvallich Peninsula. After E. B. Bailey.

Carboniferous and Permian Systems.

Carboniferous vulcanicity which was displayed on the largest scale in South Scotland, expressed itself in two ways.[1] In the earlier stages (Calciferous Sandstone, Plate I B) great *volcanic plateaux* were built up, some of which covered as much as 2,000 or 3,000 square miles, and were 3,000 feet in thickness. At a slightly later date (Scottish Carboniferous Limestone, Plate I B) these volcanoes were replaced by a large number of relatively small explosive vents or *Puys* whose ejectamenta were partly spread out on the sea-floor in the form of volcanic banks and shoals, and partly employed to build up either

[1] See particularly A. Geikie, *Ancient Volcanoes of Great Britain*, London, 1897, chapters xxiii–xxviii. A. Harker in *Handb. regional Geol. British Isles*, pp. 168–72.

composite or ash cones. These types of volcano came into prominence again in Permian times, and we shall draw upon both systems for illustrations of the processes connected with them.

Lower Carboniferous Plateau-Volcanoes.

Our knowledge of these volcanoes is supplied by two main types of evidence: firstly the great lava-fields with their occasional ash-intercalations, and secondly the agglomerate-, tuff-, and lava-filled vents through which the material of the plateau was brought to the surface.

The Lava-Fields.—What were originally five separate volcanic plateaux may be distinguished: Clyde, East Lothian, Midlothian, Berwickshire, and Solway; but the general characteristics of all are similar. The material ejected in each was mainly basalts and alkali-basalts, though orthophyres and trachytes are also found. Each plateau is constructed of a large number of relatively thin lava-flows, sometimes separated by bands of tuff and ash, which thicken towards the vents and may there become agglomerates. It is clear that for the most part the lava flowed from the orifices quietly, and was spread out as liquid streams over a large area. Sometimes it is barely more than a mass of clinker; more often it has a slaggy upper and lower surface, and a compact, jointed centre. Often it is vesicular throughout. Associated with the lavas are sills. In each plateau one or more centres can be found towards which the volcanic pile as a whole thickens, and Geikie has calculated the original slope of the lavas of the Clyde plateau—on the assumption that their base was horizontal—and finds it to be 1 in 35 near Largs and 1 in 63 near Kilsyth. But it is possible that the slopes were never so steep; for the region of greatest accumulation may well have also been that of maximum subsidence, as evidence is not wanting that the lavas at certain levels sank below the sea and were covered with ordinary sediments.

The Plateau-Vents.—The lavas of the plateaux do not appear to have been fed extensively from fissures, as was the case in the Cainozoic plateau-lavas (p. 354); but from a number of pipe-like vents which in some cases appear to be aligned as if on some belt of weakness. The smaller vents are usually fairly circular in cross-section, but the larger display an irregularity that may be regarded as the result of the fusion of two or more pipes. Many, no doubt, are hidden by the lavas of the plateaux, but a great many are known in adjacent areas from which the latter have been denuded away. The vents are recognized by their infilling of tuff and agglomerate, along with which there may be dykes and irregular masses of injected lava, the whole infilling being the product of the latest efforts of the volcano.

The greater resistance to denudation offered by the igneous material of the neck than is afforded by the surrounding strata usually causes them to rise as isolated hills (Fig. 142), but occasionally the reverse is found and the neck forms a hollow. The vents are generally bounded by nearly vertical walls, and vary in size from 100 feet to 4 miles in their greatest diameter, the larger ones no doubt being composite.

Volcanic emanations in many cases escaped by way of the vents, and have often profoundly modified the infilling material and the neighbouring country-rock.

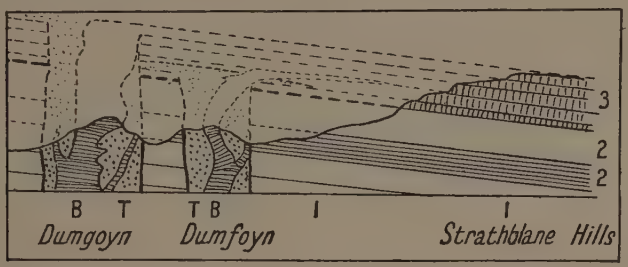


FIG. 142.—Hypothetical reconstruction of the relation of the two necks of tuff agglomerate (T), and basalt (B), forming the hills named Dumfoyn and Dumgoyn, to (3) the plateau-lavas of Strathblane Hill, Stirlingshire. These are part of the Clyde Plateau. 1 and 2, Lower Carboniferous sediments. The lavas and strata were originally horizontal. The conical hills of Dumgoyn and Dumfoyn are prominent features in the landscape. Based on Geikie.

Underground, the volcanic energies spent themselves in filling dykes, sills, laccolites and bosses, many of which are now exposed by denudation.

It is difficult to find a modern parallel to the Carboniferous plateau-volcanoes. Their products took a form that recalls the lava-plateaux of the Icelandic fissure-volcanoes rather than the lava-domes of Hawaii; but a multiplicity of pipe-like vents is found instead of the straight fissures of the former (p. 15) and the great calderas of the latter (p. 14).

The Carboniferous Puy-Volcanoes.—The plateau-volcanoes became extinct and their products sank below the sea and were covered with sediments. But at a slightly later date the Avonian sea of Southern Scotland became scattered over with small explosive volcanoes (puys), some of which were opened up within the same areas that had seen the plateau eruptions, just as these latter were in turn localized on the sites of Old Red Sandstone volcanic districts.

The puy-type of volcano derives its name from the well-known puys or small volcanic cones of the Auvergne district in France (Fig. 144*a*). Geikie states that "volcanoes of this type form conical

hills, generally of small size, consisting usually of fragmental materials, sometimes of lava." Owing to their smallness and to the nature of their material, puys are readily destroyed, with the exception of the necks which may be the sole witness to their former presence.

The Carboniferous puy-volcanoes can usually be separated from the members of the plateau-suite by the interbedded fossiliferous strata which prove them to be of a later date.

As a rule the puys have smaller vents and are grouped together over far smaller areas than those covered by the plateaux-volcanoes, and lie in many cases in the intervening districts.

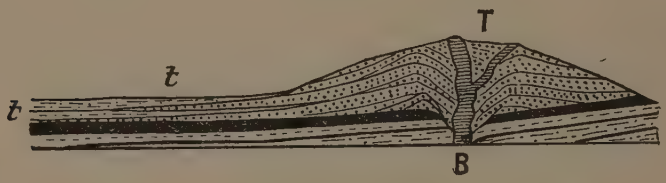


FIG. 143.—Diagram-section across Saline Hill Volcanic Vent, Fifeshire. Shows the bedded tuffs (*t t*), conformable to the seams of coal and ironstone worked under Saline Hill, passing into the tuffs (T) of the vent, pierced by basalt (B). Based on Geikie.

In many parts the chief record of this igneous activity consists of beds of tuff, sometimes fine, sometimes coarse, interbedded with ordinary sediments with little or no disturbance of the stratification; showing, it is thought, that a great number of small explosive eruptions took place whose products fell intermittently on to the sea-floor, usually only over a small area in each case. In the Saline Hills of Fife one can see the volcanic ejectamenta in direct relation to the vent from which they were derived (Fig. 143).

At the maximum development, lavas were associated with ashes, but even then usually in subsidiary amount. There are four areas in Scotland, however—the Burntisland district, the Bathgate Hills, North Ayrshire, and Liddesdale—where the eruptions piled up actual cones or long connected banks and ridges; and here lavas and tuffs follow one another in rapid succession. For example, between Burntisland and Kirkaldy, out of 1,500–2,000 feet of rock some 1,200–1,600 feet are igneous. The flows average perhaps 20–30 feet in thickness; some show columnar jointing, some are amorphous; interspersed are agglomerates, ashes, limestones, shales, etc. It is clear that no great volcanic dome or plateau was formed in any district, but rather that the sea-floor sank as the volcanic products were piled upon it, for the lavas and ashes take their place between marine deposits just as if they were normal sediments (Fig. 143*t*).

When we turn to the volcanic necks we find every stage represented, from the neck in direct connection with its outpourings, as in the Saline Hills above cited (Fig. 143), to the stump completely isolated by subsequent denudation. Many of these stumps are found in the areas where their outpouring are known to exist, but others are in districts where the latter have been completely removed by erosion, and the neck is the sole evidence of former vulcanicity. It is difficult to decide in this case to what period it may belong. This is particularly so in South Scotland since similar puy-volcanoes, ejecting similar material, were in action both in the Lower Carboniferous and in the late Carboniferous or Permian periods; but as we are concerned with the processes that the necks display it is not of prime importance to distinguish the two series.

So-called Permian Puy-Volcanoes.—These may be divided into:

(*a*) *The South-Western Group*, in which some of the vents can be proved by their intercalation in so-called Permian strata to be of that age, though others of them are quite isolated and therefore only dated by inference.

(*b*) *The East Fife Group*, in which some 80 necks pierce the Carboniferous rocks. Here, however, denudation has destroyed the lavas and ashes thrown out of the volcanoes, and the volcanic necks have alone been preserved. The Permian age of these necks has been inferred from the similarity of their petrological and other characters to those of the South-Western Group; but some doubt has been cast upon this inference recently, for in the case of Largo Law (Fig. 144*b*), one of the largest of the East Fife necks, the lavas and ashes have been found by D. Balsillie to be interbedded with, and therefore contemporary with, Lower Carboniferous strata.[1] This observer adduces evidence in favour of regarding the other East Fife necks as also dating from that epoch; but as in their case the evidence is inconclusive we may follow the older authorities in regarding them as Permian.

Some of the larger necks, as for instance Chalto Hill (597 feet), stand out as grass-covered conical hills resembling active volcanoes of the Vesuvian type (p. 14), but this superficial resemblance is misleading;[2] for all trace of the volcanic cones has gone, and the present land-surface cuts through the platform on which the volcanoes stood. In fact the conical hills, far from being original volcanic cones, are formed by the cylindrical plugs of tough igneous material that filled

[1] D. Balsillie, *Geol. Mag.*, 1923, p. 531, and G. W. Tyrell, *Geol. Mag.*, 1924, p. 142. A. Harker, *op. cit.*, classes them with the Carboniferous.

[2] Largo Law is the finest example of these cone-shaped hills, but is of Lower Carboniferous age (Fig. 144*b*).

the throats deep down to the very base of the original orifice; and it is merely by virtue of the igneous material being more durable than the surrounding country-rock, that they form prominences in the present landscape. Fig. 144 illustrates this point; in the successive sketches *a* to *d* the state of erosion is progressively greater, *d* representing the stock or deep-seated feeder of a volcano now standing up as a hill.

FIG. 144.—Denudation of Puy-Volcanoes.

(*a*) *Survival.* Early stages in the denudation of a recently extinct volcano, the trachytic Puy-de-Dôme in Auvergne.

(*b–d*) *Resurrections*, i.e. the relics of ancient volcanoes that have been buried under newer strata, and resurrected by the denudation of the same; they form hills merely by virtue of the hardness of the volcanic material. All those illustrated are Carboniferous or Permian in age.

(*b*) Dissected cone of agglomerate and tuff with dykes of basalt. X is a basalt that may have been a lava-flow. Largo Law, Fife.

(*c*) Dissected neck, composition as above, Binn of Burntisland, Fife.

(*d*) Dissected plug or stock of trachyte. North Berwick Law, Haddingtonshire.

The Permian vents are now isolated, but when they were active, it is possible that their ejecta formed a continuous cover to the whole region, which was probably no longer under the sea, as in Lower Carboniferous times, but part of the Hercynian continent (p. 73). Rising above this volcanic plateau we may picture groups of small cones, an arrangement closely repeated in the Auvergne to-day.

As examples of dissected volcanoes the East Fife necks [1] are most instructive; for the erosion of the present coast has displayed remarkably clearly their intimate structures, both in section on the cliffs and

[1] A. Geikie, *Ancient Volcanoes*, 1897, vol. ii, chap. xxxi, and "Geol. of Eastern Fife," *Mem. Geol. Surv.*, 1902.

in plan on the foreshore (Figs. 145, 146). Here are laid bare in detail those vital parts of a puy-volcano which in the nature of things are inaccessible for study in an active or recently extinct vent.

The Throat of a Puy-Volcano.—The cross-section of the majority of the orifices is subcircular or oval; but occasionally a vent is found that has approximated to a fissure in shape. The necks vary in size from ten yards to half a mile or more across. Each is bounded by vertical walls, the country-rock adjoining it being, as a rule, violently distorted, though at no great distance away the strata pursue their courses undisturbed. A remarkable characteristic is the way in which the location of the vents is usually independent of faults or other structural features in the surrounding rocks (Fig. 145). These remarks all apply equally to the Lower Carboniferous and to the Permian necks.

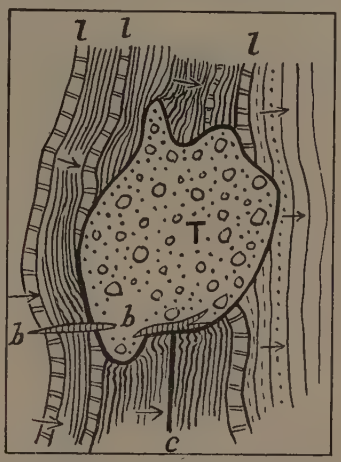


FIG. 145.—Plan of neck (about 50 yards in diameter) on beach near St. Monan's. Redrawn from Geikie, *Ancient Volcanoes*. By permission of Messrs. Macmillan & Co., Ltd.

T, tuff of neck; *b*, basalt-dykes; *c*, coal; *l*, limestone in shales, etc.

Daubrée has instituted the name *diatreme* for such volcanic channels, drilled by gaseous explosions through the crust, irrespective of the arrangement or composition of the country-rock. In Fife some of the diatremes were formed by a single paroxysmal explosion that punched a small hole, into which fell back the broken debris of the surrounding strata without the addition of ashes or lava. The majority were, however, the scene of repeated eruptions, and are plugged with a mixture of agglomerate, tuff, and fragments of country-rock, through which lava has risen and solidified as irregular masses or dykes. The riddling of the agglomerates by basalt dykes is perhaps most strikingly displayed in the great Carboniferous neck of Burntisland. In many cases also the dykes pass out of the neck into the neighbouring strata. In one or two instances, e.g. the Kincraig Neck, larger masses of basalt appear to represent lava that rose and filled the bottom of the crater (Fig. 146). This is deduced from the direction of the prisms produced by the columnar jointing of the basalt. Such prisms are always directed at right angles to the cooling surface, and in the cases under discussion the columns are approximately vertical and the cooling surfaces therefore horizontal. No

case is known in which a Permian vent has been completely plugged by lava.

The igneous fragments in the pyroclastic rocks are of two types. Firstly, there are the large angular blocks, finer pebbles and sand produced by the action of the explosions on already-solidified lavas. Secondly, rounded "bombs" and "pumiceous sand" are found which have resulted from the expulsion of liquid magma into the air. In addition to the above constituents in the necks, crystal of minerals which are foreign to the lavas (xenocrysts) and which may represent

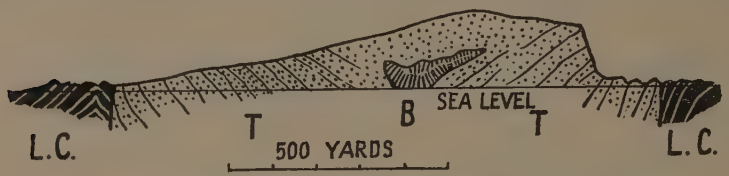


FIG. 146.—Section across Kincraig Neck (Elie, Fife) to true scale.

Based on Geikie, *Ancient Volcanoes*. By permission of Messrs. Macmillan & Co., Ltd.
L.C., Lower Carboniferous sandstones, shales, etc.; T, tuffs and agglomerates of the neck; B, basalt with more or less vertical columnar jointing.

fragments of older rocks caught up by the ascending magma, are found in the dykes and in the agglomerates and tuffs. Chips of fossil wood are sometimes present, a feature that suggests the growth of forest over the volcanic cones between successive eruptions.[1]

The pyroclastic material ejected by each explosion fell, in part, on the outer slopes of the cone (since destroyed by erosion) and, in part, into the neck. In both cases it accumulated at the angle of rest of loose ashes and scoria, perhaps 25° to 30°. As would be expected on this account, the agglomerates and tuffs that fell back into the Fife vents, are found to have a concentric bedding, dipping inwards, but the angle of dip is generally far steeper than 30° (Fig. 146). This is best explained by the assumption that the material acquired its present inclination through being dragged down by the subsidence of the whole column within the vent. The correctness of this inference is borne out by the sharp inward dip displayed in nearly all cases by the country-rock immediately surrounding the neck. One would expect to find the strata forming the sides of the explosion-chimney directed upwards, whereas the opposite is almost invariably the case. Hence subsidence of the volcanic plug may be counted as one of the normal characteristics of explosion-vents, as it also appears to be in lava-cone volcanoes (pp. 362–8).[2]

[1] In the Carboniferous vents the wood is usually coniferous, and of a type quite distinct from the plants of the lowland-swamps of that period. Hence it is inferred that the well-drained volcanic slopes supported a distinctive flora.

[2] See C. Fenner's account of the subsidence-crater of the great 1912 eruption

Mesozoic Vulcanicity.

There was no igneous activity of any importance in Britain during the Mesozoic era.

Cainozoic or Tertiary Vulcanicity.

The Igneous Province of North-Western Britain and Ireland.—The Tertiary rocks of North-Western Britain and North

FIG. 147.—Tertiary Vulcanicity.

Basalt-plateaux stippled; plutonic masses, i.e. central volcanoes, full black; regional dykes, straight lines, each representing many individual dykes, except in the South-East. Based on Bailey, Holmes and Harker.

Ireland are almost exclusively igneous in origin. The principal areas where they occur in force at present are Antrim, Arran, Mull, Ardnamurchan, Rum, and Skye (Fig. 147); but there is strong evidence that these districts form part of a much larger "Brito-Icelandic province" (Judd), over which igneous activity prevailed

of Katmai, in Alaska, *Journ. Geol.*, vol. xxviii, 1920, pp. 569–606; J. S. Diller, *Journ. Geol.*, vol. xxxi, 1923, pp. 226–7, *re* Crater Lake of Oregon; Anderson, *Journ. Geol.*, vol. xvi, 1908, p. 499, *re* Mount Aso in Japan.

(Fig. 72). Much of this region has since foundered beneath the Atlantic. The province includes not only the British region, but also the Faroe Islands, Iceland, and probably parts of Greenland, Spitzbergen, and other Arctic lands. In Iceland igneous activity has continued to this day.

The province exhibits the best British examples of volcanoes built up predominantly of lava. Two types appear to be represented:

(1) *Fissure-volcanoes* of the *Icelandic* or *Laki* type,[1] in which lava wells out at the surface through fissures or from numerous small craters arranged along a fissure, successive flows building up a plateau (pp. 15, 16). Explosive eruptions are usually in abeyance, though small craters may line the fissure (crater-rows) (Fig. 8).

(2) *Central-vent volcanoes* of the *Hawaian* or *Kilauea* type (see p. 14) with gently sloping cones (lava-domes) (Fig. 7). Here the volcanic pile is for the most part built up of successive flows of mobile lava emitted from a central vent or parasitic vents, though this method of eruption may sometime alternate with paroxysmal explosions. Often there is a central depression or caldera, like the one containing the lava-lake of Kilauea. This type is also abundantly represented in Iceland.

On account of the detailed studies of the British region made by the late Prof. Judd, Sir Archibald Geikie and other officers of the Geological Survey, more particularly Dr. Harker and Mr. E. B. Bailey, much light has been shed on the structure and mechanics of these two types of volcanoes.[2] In modern examples only surface manifestations can be examined, but here denudation on a vast scale has dissected not only the superficial volcanic rocks and their associated sills, sheets and dykes of intruded material, but also has cut deeply into the great plutonic masses that solidified below the cover of lavas at each centre of vulcanicity (Fig. 147).

Regional Vulcanicity.—*Lava-plateaux* of a very similar character are found throughout the British portion of the great province, and present a characteristic terraced type of rolling topography.

[1] Thoroddsen states that every type of volcanic activity can be recognized in Iceland, and enumerates eighty-seven examples of major eruption-fissures and sixteen of lava-domes (see E. B. Bailey, *Geol. Mag.*, 1919, p. 471). Hence the term *Icelandic type* is meaningless, whereas the term *Laki type* is appropriate, since Laki is an excellent example of a fissure-volcano, though according to Tempest Anderson the volcano should bear the cacaphonous name of Skaptár Jökull (Tempest Anderson, *Volcanic Studies*, p. 122).

[2] Geol. Survey maps of Skye and Mull. A. Geikie, *Ancient Volcanoes of Great Britain*, Book VIII; J. W. Judd, *Volcanoes*; A. Harker, *Igneous Rocks of Skye*; E. B. Bailey and others, "Tertiary and Post-Tertiary Geology of Mull, Loch Aline and Oban," *Mem. Geol. Survey*, 1924; *Summary of Progress Geol. Survey*, 1909–1914; Tempest Anderson's *Volcanic Studies*, part referring to Iceland, Ireland, and Idaho, U.S.A.

The igneous activities that gave rise to them extended over such large areas (Fig. 147) that they deserve the term *regional* in distinction from the *local* phenomena (to be treated later) which are restricted to certain centres. The lava-plateaux consist of innumerable basaltic flows that vary severally from a few feet to perhaps 150 feet in thickness (Fig. 148). Individual sheets may present vesicular, slaggy, and massive portions, the latter often exhibiting columnar jointing, as in the famous Fingall's Cave at Staffa. The lavas were poured out on land, and where individual flows remained uncovered for long

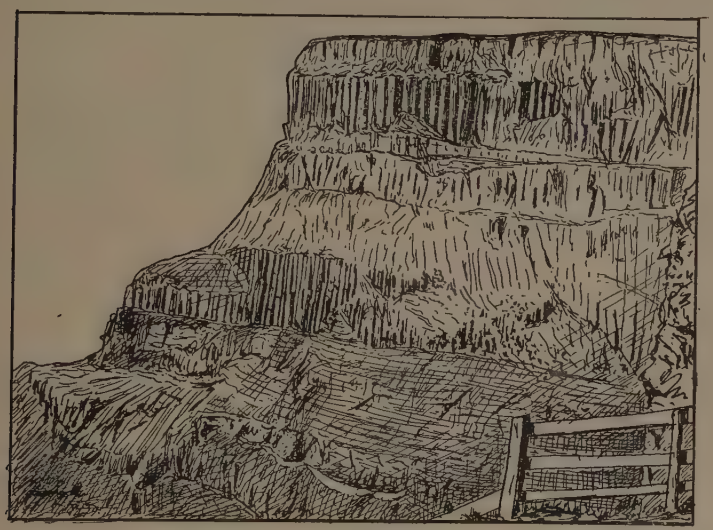


FIG. 148.—Basalt plateau-lavas. Pleaskin Head, Antrim. Sheets of columnar basalt with softer "boles" or ancient lateritic soils between them. (After photo by Tempest Anderson.)

enough, their surfaces became weathered to red residual clays known as bauxites and lithomarges (p. 26). In Ireland the succession of lavas is broken by extensive deposits of these types (Fig. 148), and it is clear that there was at least one long pause in the vulcanicity. On these soils a forest-growth sprang up, remains of which are occasionally preserved as fossils. It is by reference to the latter that the Lower Cainozoic age of the lavas has been determined. Such soils are not forming here at present, and the climate was quite different from that of to-day, and was probably of a semi-arid tropical type.

Though individual flows are thin, collectively the lavas amount to several thousand feet in thickness both in Skye, Mull, and Antrim. According to Harker, the plateaux of Skye and perhaps elsewhere

are not exclusively built up of lava, but contain massive sills of similar basic material that have been injected between successive flows. In his view, the combined thicknesses of the sills equal the thickness of the lavas; but other observers, especially Bailey and his associates in the case of Mull, regard the massive portions of the volcanic pile as the central parts of thick lava-flows.

In South-Eastern Mull widespread lava-flows resembling the plateau-lavas appear to have been poured out by the great Mull volcano (p. 359) which was a central-vent volcano of the Hawaian type; whereas over the rest of the island the flows may have issued from fissure-vents as in Skye. Such an association of the two types of eruption is seen at the present day in Iceland.[1]

Throughout the whole British igneous province (Fig. 147) the lava-plateaux are reinforced by innumerable narrow vertical dykes trending as a rule to the north-west or north-north-west. Some of these represent feeders up which the magma made its way to supply the surface-vents or the underground sills; but the majority were injected late in the history of the area and may never have reached the surface. The dykes occur in "swarms" in Mull and Arran and extend beyond the limits of the volcanic region, even as far as England. Their uniform composition and constant direction are remarkable features, and associate them very definitely with the regional type of vulcanicity.

As already pointed out, the isolated areas of lava-plateaux in Britain must be regarded as surviving portions of a vast region ranging from Antrim to Skye and beyond, much of which has since sunk below the sea, so that we do not know its limits. It was, however, a region comparable in size and in the magnitude of its volcanic activity with the Deccan Basalt-plateau (200,000 square miles) or with the Snake River plains of Idaho (300 miles long), both being areas where recent lava-fields have been extruded through fissures or from numerous small vents aligned along fissures. Harker regards the regional phenomena as pointing to a very large area of the earth's crust having been under the influence of tensional strain that developed cracks through which successive injections from a huge reservoir of uniform magma were made.[2] In his words (p. 413): "The strain . . . was relieved first by the uprise of molten magma through fissures communicating with the surface, then by the uprise of magma which did not find exit but was injected along bedding planes; only after this did bodily displacement of the solid rock masses come into play in the form of faulting and tilting."

[1] Most of the Mull plateaux-lavas may in reality have come from the central vent.

[2] See also J. W. Evans, *Proc. Geol. Soc.*, vol. lxxxi, 1925, pp. ci–ciii.

Local Vulcanicity.—The monotony of the lava-plateaux is broken in Skye, Rum, Mull and Arran by centres of *local* igneous activity that are characterized by a far greater diversity of rock-types, which range from ultra basic to acid in composition, and from volcanic to plutonic in their modes of origin. This variety combined with the massive nature of many of the plutonic rocks gives rise to diversified mountainous scenery, in strong contrast to the monotony of the lava-plateaux.

The *local* type of igneous phenomena appears to be directly related to compressional earth-movements.[1] The specialization of rock-types in these centres stands also in marked contrast to the uniformity of composition displayed by the various elements that constitute the lava-plateaux. Harker remarks that the limitation of such specialized rock-types to the *local* centres is so consistent a feature that he considers it proved "that the distinct foci at which activity was from time to time localized, were also the principal centres of magmatic differentiation." By the latter term we mean the process by which two or more rock-magmas of distinctive composition are derived from a common source.

Outline of Igneous Activity in Skye and Mull

We may now consider the history of two of the local centres, namely Skye and Mull. This history cannot be divorced entirely from that of the neighbouring lava-plateaux.

i. Skye.[2]—Cainozoic vulcanicity in Skye opened with a few small paroxysmal eruptions of volcanic ash, tuff and agglomerate. After this came the *first great phase* of regional activity, in which countless streams of mobile lava were poured out quietly from subparallel fissures to form the lava-plateaux. The fissures, filled by the last flow of magma, are now displayed as north-west or north-north-west dykes (see p. 354). As is the case in many of the Icelandic eruptions of to-day, there was frequently no fault-displacement along the fissures. As the lavas are but seldom well-exposed, the actual continuity of feeder and lava-flow has rarely been demonstrated.

The *second great phase* of igneous activity in Skye was not regional, but localized in the central part of the island. Here deep-seated or plutonic intrusions took place (Fig. 149), beginning towards the south-

[1] For the connection between types of vulcanicity and earth-movement, see Marcel Bertrand, "Sur la Distribution Geographique des Roches Eruptives en Europe," *Bull. Soc. Geol. France*, Sér. 3, vol. xvi, 1888, pp. 573–617, and Harker, *op. cit.*, p. 412, and *Q.J.G.S.*, vol. lxxiii, 1918, pp. xciii–xcvi. F. Loewinsson-Lessing, *Bull. Geol. Soc. France*, Sér. 4, vol. xxiii, 1924, pp. 142–57.

[2] A. Harker, "Igneous Rocks of Skye," *Mem. Geol. Survey*, 1904.

west with *ultrabasic* rocks, followed by *basic* (gabbro) in the Cuillins, and eventually at a later date by *acid* (granites) of the Red Hills. Thus the centre of activity shifted towards the north-east concurrently with the change in composition of the magma. Though the cover of lavas into which the gabbro and the granite were intruded has been denuded away, the under-surface of the plutonic masses can in places be traced, showing that both are in part laccolitic in shape (Figs.

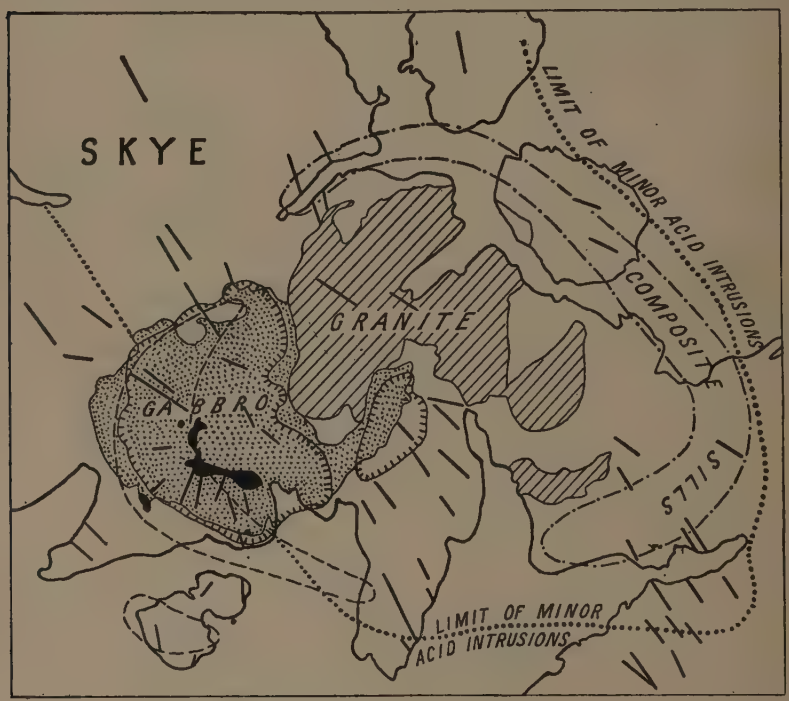


FIG. 149.—Major and some minor intrusions in Skye.

Peridotite laccolites full black; Gabbro of Cuillins stippled; Granite of Red Hills diagonal shading; limit of minor acid intrusions, line of dots; basic dykes, straight lines; limit of basic cone-sheets, continuous line with short ones at right angles; limits of ultrabasic dykes, broken lines; limit of composite sills (basic and acid), dots and dashes.

9, 150, and p. 16). The granite, however, in some places breaks vertically across the country-rock and thus locally approaches a *boss*-like form. In the case of the granite the magma was introduced as more than one intrusion (Fig. 150).

The *third great phase* of activity was that in which the majority of the *hypabyssal* or "*minor*" intrusions took place. Though small individually, these collectively amount to a huge volume of rock.

In this phase, intrusions belonging to the regional and local suites have to be distinguished. The rocks of the *regional* suite are petrographically as monotonous as the plateau-lavas they invade, being without exception dolerites; but in the *local* suite the variety in rock-composition is even greater than that found in the plutonic intrusions. Yet within the local suite it is clear that the hypabyssal varieties of a given composition are related in space to the plutonic centres of similar composition. Thus there is a set of acid dykes and sheets centred on the granite, whereas the basic ones are confined to the gabbro-area (Fig. 149).

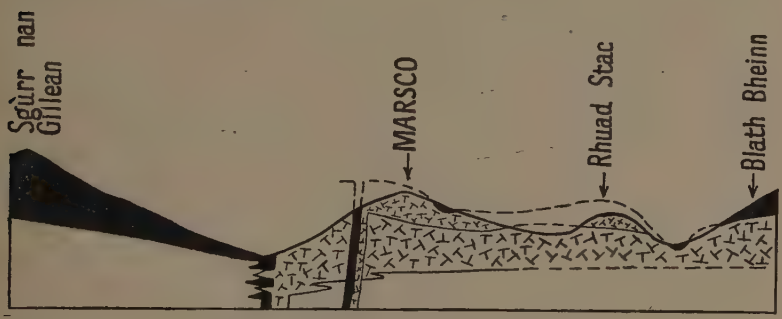


FIG. 150.—Plutonic laccolites of Skye.

Diagram-section to show the laccolite habit of the Gabbro, full black; and of the two varieties of granite (T_L); country rock, white. Based on Harker.

Five episodes may be distinguished in this third phase:

(*a*) *Regional Injection of the Basalt-plateau by a great Series of Dolerite Sills* ("*the great sills*").—This renewal of activity on the regional scale appears to have been an attempt to repeat the regional volcanic phase, but so far as is known, the magma did not reach the surface. According to Harker, innumerable sheets of dolerite were thrust along the planes separating successive lava-flows,[1] and it is these that by their superior hardness give the characteristic terraced outline to the basalt-plateaux. Their injection he estimates more than doubled the thickness of the plateau in Skye, the lavas and sills together being in places even now over 3,000 feet thick. There is no evidence to suggest that this sill-injection accompanied faulting; but the magma appears to have welled quietly up through fissures. Many of the sills display a marked columnar jointing, the columns being at right angles to the surfaces of cooling. Even in sills 100 feet thick the columns are continuous from base to summit.

(*b*) *The Local Injection of Dykes and Sheets of Acid Composition.*—As already pointed out, this series of intrusions is centred on the

[1] Criticism of this view has already been referred to (p. 354).

granite, but there is a marked tendency for the dykes to be drawn from a radial arrangement towards a north-west to south-east direction. This shows the influence of the regional phenomena next to be discussed.

(*c*) *The Regional Injection of North-Westerly Dykes.*—At this time the basalt-plateau was broken into blocks that moved differentially, and the characteristic structure—that of gently-tilted plateaux divided by lines of fault—was established over the greater part of the island, and henceforth the molten magma as it rose was confined to north-westerly fissures, for it neither spread laterally among the country rocks, nor, so far as we know, was it poured out at the surface. The latter point must remain uncertain, for the upper part of the lava-pile has been destroyed by denudation.

(*d*) *The Local Injection of Basic Minor Intrusions.*—These are found within the gabbro-area. They are tangential and radial dykes, and centrally-inclined sheets, known as cone-sheets (Fig. 9 c). The latter are so called because each sheet forms part of an imperfect inverted cone-shaped intrusion, concentrically located with regard to an underground focus of intrusive activity. On gently sloping ground, therefore, they present narrow arcuate outcrops, but vertical sections show them as dipping steeply towards a common centre (Fig. 152). Their intrusion is obviously connected with the relief of some strain, possibly an upward tendency at the point to which the sheets are concentric.[1]

(*e*) *The Local Injection of Ultrabasic Minor Intrusions.*—This took place in the south-western area where the ultrabasic plutonic rocks are found, and appears to have been the final manifestation of igneous activity in Skye (Fig. 149).

If then we examine the local suite, it is clear that in the plutonic phase activity began in the south-west with ultrabasic intrusions. The centre of activity during this phase moved towards the north-east, while the rock-types became increasingly acid. During the hypabyssal phase exactly the reverse took place, so that intrusive activity ended where it had begun, and with rocks of practically identical composition.

ii. Mull.[2]**—A type-example of a Dissected Lava-dome Volcano** (Plate II and Figs. 151, 152).—Whereas in Skye, owing to enormous denudation, little is known of the surface-phenomena connected with the local igneous centre, in South-East Mull we have exposed for inspection, not only the roots of a great volcano,

[1] See also E. M. Anderson in *Tertiary and post-Tertiary Geology of Mull*, etc., p. 11. Harker uses the term "inclined sheets."

[2] E. B. Bailey and others, "Tertiary and post-Tertiary Geology of Mull, Loch Aline, and Oban," *Mem. Geol. Surv.*, 1924, with full bibliography.

but also some part of the superstructure of lavas and volcanic breccias which have here escaped erosion. The volcano, when active, appears to have risen as a gentle dome above the surrounding lava-plateau, to the formation of which it largely contributed. For the greater part of its history it was a vent of the Kilauean type (p. 14, Fig. 7) with gently rising slopes of lava [1] and a central depression (caldera) in which at times lay the waters of a crater-lake, while at other times subaqueous or subaerial eruptions covered the floor of the caldera with lava. Yet the tranquillity of the lava-cone was intermittently shattered by paroxysmal outbursts during which it must have assumed the appearance of a vent of the Vesuvian type.

Thanks to the labours of E. B. Bailey and his co-workers,[2] we are now able to trace in outline the successive stages of the growth of the Mull volcano. It must, however, be understood that owing to the extreme complexity some of their conclusions are susceptible to other explanations, a statement that they would no doubt be the first to endorse. Their memoir is the source of the following account.

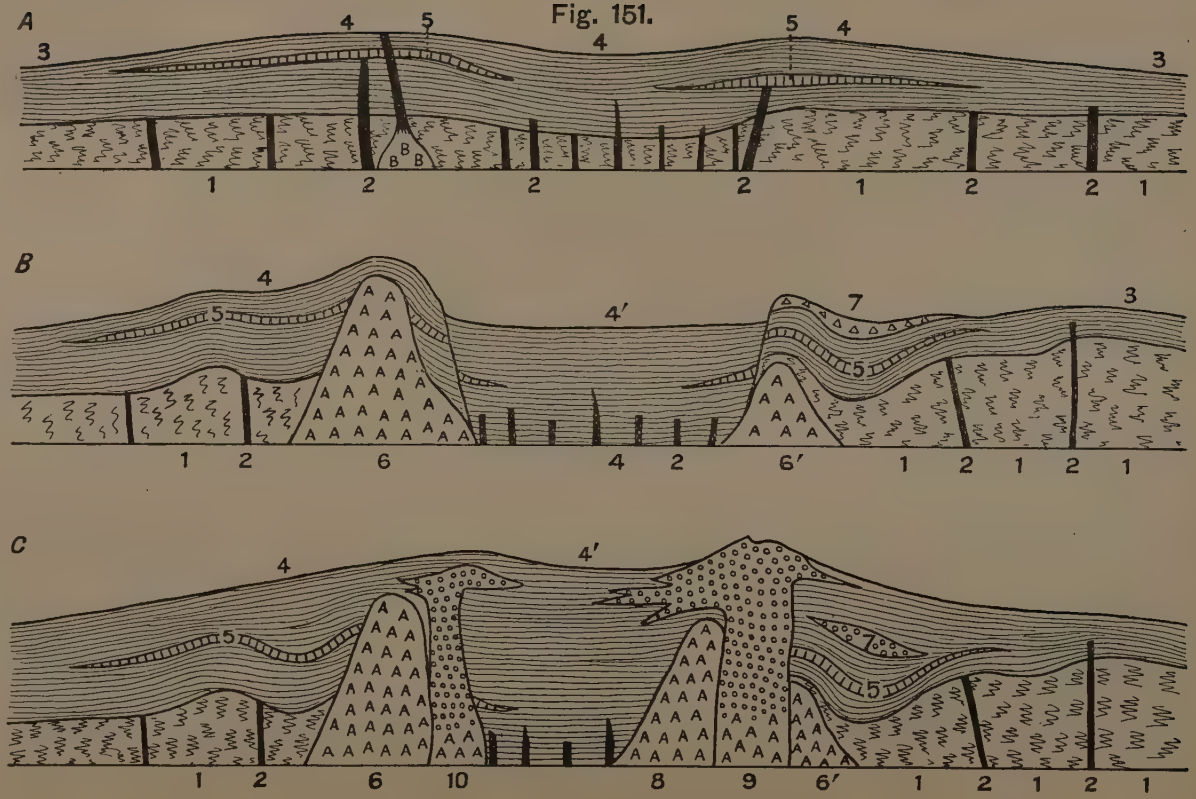
Two distinct magmas seem to have been drawn upon in turn for the supply of surface-vents and of intrusions, both great and small. One was basic and may be termed the basic or basalt-gabbro magma, the other was much more acid and gave rise to rhyolites, felsites and granophyres (acid or granophyre-magma). Other intermediate and allied types are found in subsidiary amounts. The various intrusions are indicated for the sake of simplicity in the generalized map (Pl. II) and sections (Figs. 151, 152) as belonging to either one or other of the two magmas.

First Stage.—As in Skye, volcanic activity appears to have opened with small explosive eruptions quickly followed by the quiet outpouring of *plateau-lavas* on a huge scale, with hardly any explosive episodes (Fig. 151A). These lavas are basalts similar to the plateau-lavas of Skye; and may, like them, have been in part fed from fissures. As the *local* centre is approached the early plateau-lavas appear to be followed upwards by others of slightly different types whch are restricted to the south-eastern part of the island, and may be termed the *central* types, for they appear to have been poured out from a central vent which was located somewhere in the region of Beinn Chaisgidle (Pl. II, C.1). The site of this mountain may be regarded as the focus of the early volcanic activities, and is termed C.1 (standing

[1] By analogy with the Hawaian domes, the Mull volcano, with a base some 20–25 miles across, may well have risen 7,000 or 8,000 feet above the neighbouring basalt-plateau. See Fig. 7.

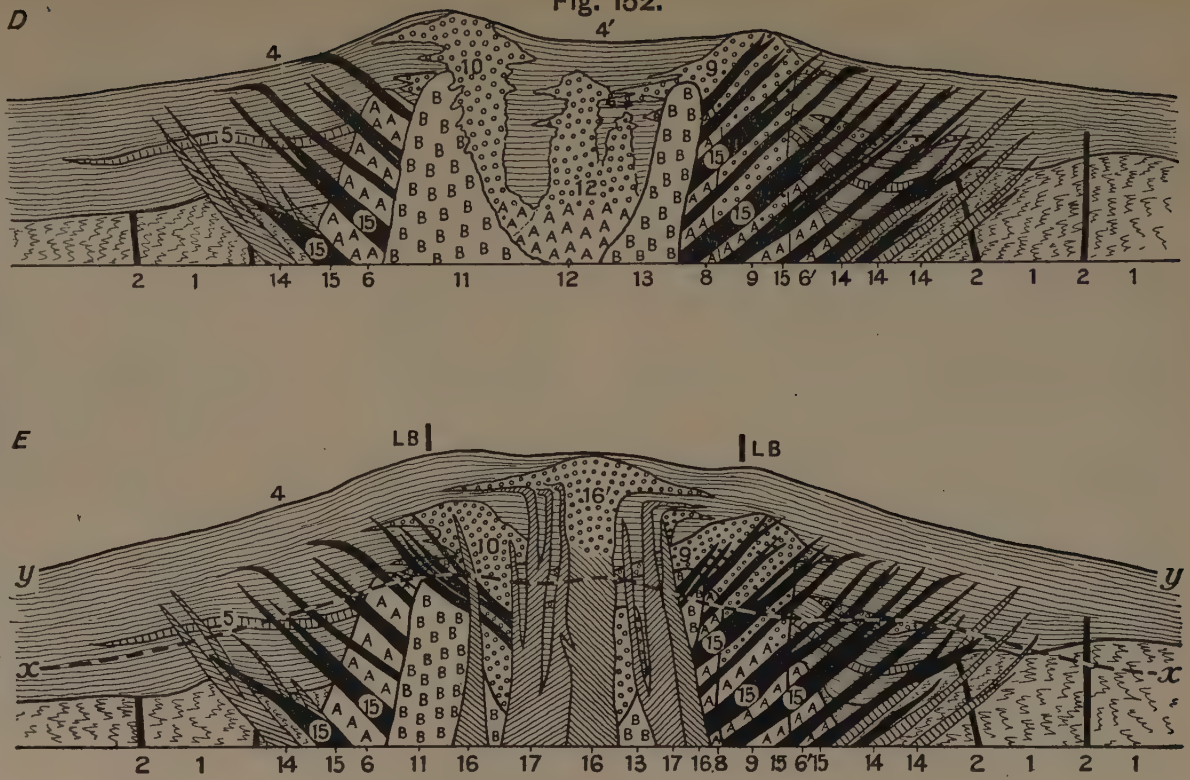
[2] Including in particular the late C. T. Clough, who also contributed to Harker's work in Skye, W. B. Wright, J. E. Richey, G. V. Wilson, and E. M. Anderson.

Fig. 151.



1. Pre-Tertiary rocks.
2. Feeding dykes.
3. Plateau-lavas.
4. Central lavas and 4′ lavas of the Caldera (some pillow-lavas).
5. Mugearite lavas.
6. Derrynaculen and 6′ Glas Bheinn Granophyres.
7. Coire Mor agglomerate.
8. Torness Felsite.
9. Scurr Dearg vent-agglomerate and feeder.
10. Vent agglomerate.
11. Ben Buie gabbro.

Fig. 152.



12. Vent-agglomerate of caldera.

13. Beinn Bheag gabbro.

14. Early acid cone-sheets.

15. Early basic cone-sheets.

16. Acid ring-dykes with 16′ agglomerates at surface.

17. Basic ring-dykes with lavas at surface.

LB, LB, outer limits of area in which late basic cone-sheets (omitted for simplicity sake) were intruded, some cutting and some cut by the ring-dykes 16 and 17.

xx. Present generalized surface-profile.

yy. Hypothetical outline of the volcano at its maximum size when Caldera 1 was the principal focus of activity.

A, and right-diagonal shading, acid intrusives.

B, full black, and left-diagonal shading, basic intrusives.

FIGS. 151 and 152.—The development of the 1st Caldera of the Mull volcano. (C 1 on Plate II.)

for 1st Caldera). Centred on it lies a district some five miles across in which at various levels in the sequence, pillow-lavas are found (p. 342). As the pillow-structure is now generally acknowledged as evidence of the subaqueous solidification of a lava, its presence here has been regarded as implying the existence of a crater-lake occupying from time to time a central subsidence or caldera below the waters of which the lavas were extruded.

The focus C.1 functioned over a long time, for not only does it include the pillow-lavas, but many of the principal intrusions and many of the main structural lines are ranged in an arcuate fashion around it. At a comparatively late stage its place was taken by a second subsidence lying slightly farther to the north-west, and centred on a point, C.2, at the head of Loch Ba.

In the earliest stage, then, the volcano may be visualized as a low lava-dome passing insensibly into the surrounding lava-plateau. Even at this stage a central subsidence was marked by a large caldera. To quote Bailey, "the picture that rises before one's eyes is of the caldera-sink of Kilauea with its movable floor; only one must imagine a Kilauea with intermittent periods of repose during which the fires of Halemaumau gave place to the waters of a lake." [1]

The *Second Stage* [2] is ushered in by the appearance of the first of the arcuate intrusions known as *ring-dykes* (Fig. 151B, 6 and 6′). These structures appear to be connected with the central subsidence, and in their most perfect form each constitutes a steep-sided dyke-like body tending to have a more or less circular ring-shaped outcrop. They must be regarded as intrusions along arcuate lines of weakness [3] developed by the central subsidence. The Loch Ba ring-dyke, though intruded late in the history of the Mull volcano (see p. 365), may be cited here as the most perfect example known (see Plate II, 14). The earlier attempts at ring-dykes in Mull were large plutonic intrusions displaying the ring-like arrangement only by their roughly arcuate alignment. Composed of acid material, they are known as the Glas Beinn and Derrynaculen Granophyres (Fig. 151B, 6 and 6′, Plate II, 1 and 2). Their characteristically deep-seated structures betoken consolidation below a great pile of lavas. They lie outside, but in close relation to the central caldera, C.1, and their intrusion appears to have led to the development of a series of concentric arcuate folds in the lavas of the volcanic dome (Fig.

[1] *Op. cit.*, p. 99. Halemaumau = Eternal Fire.

[2] The stages must not be regarded as sharply defined. They overlap with regard to certain phenomena, e.g. the superficial appearance of the volcano may have remained as described above throughout the second stage.

[3] Such as a *ring-fault* or *ring-fracture* (*Kreisbrüche*). C. T. Clough, H. B. Maufe, and E. B. Bailey, *Q.J.G.S.*, vol. lxv, 1909, p. 611, and E. B. Bailey, *Geol. Mag.*, 1919, p. 466.

151B). It is thanks to this corrugation that the base of the lavas and the subjacent rocks have been brought near enough to the surface to allow erosion locally to lay them bare in the very heart of the volcanic pile.

The *Third Stage* was a protracted one and may be called the explosive phase, though the paroxysmal eruptions alternated with the quiet outpouring of lavas. Concurrently, further deep-seated and irregular ring-dykes were being intruded along with the earlier members of the great suite of *cone-sheets* (p. 358) which form the most striking feature of the Mull volcano. The following appear to have been the principal episodes in the explosive stage.

(*a*) Explosive vents opened up, which threw out coarse material that we now see as breccias or *agglomerates* in the neighbourhood of Coire Mor, to the north-east of the Central Caldera (Fig. 151B, 7; Plate II, 3.) The agglomerates consist of blocks of gneiss, granophyre, gabbro, sandstone, basalt, and rhyolite, this last probably being the lava associated with the explosive vents themselves.

The Coire Mor deposits appear to have been accumulated in the innermost syncline of the series of arcuate folds just referred to, and for this reason are to be distinguished from the vent-agglomerates. The latter represent volcanic ejecta that fell back into vents which broke transgressively through the volcanic pile, more or less along the margin of the central caldera-subsidence. Where they occur outside this limit, blocks of gneiss are common among their fragments, and are frequently of great size.[1] These "external vent-agglomerates," of Sgurr Dearg (Fig. 151C, 9, Plate II, 15) and elsewhere, are distinguishable from others inside the caldera (see below), in that the latter are for the most part free from gneiss fragments. A possible explanation is that subsidence had already carried the gneissic floor of the central region below the level at which explosions originated.

It may be pointed out here that these early paroxysmal explosions seem to have been connected with an acid magma. They may have followed very closely upon the intrusion of the granophyres of the Second Stage.

(*b*) The *early acid* and the earlier members of the *early basic cone-sheet* suite began to be injected (Fig. 152D, 14 and 15). They are centred on C.1 in the south-eastern caldera, and, roughly speaking, the farther they lie from the centre, the earlier the period of injection to which they belong.

(*c*) The enormous *plutonic intrusions* of *gabbro*, forming Corra Bheinn, Ben Buie and Beinn Bheag (Fig. 152D, 11 and 13) rose after the manner of ring-dykes, the two former just outside, the

[1] One mass of gneiss has an outcrop 200 yards across.

latter just inside the margin of the central subsidence (Plate II, 5, 6 and 7 respectively).

(*d*) A suite of *vents*, mostly within the limits of the central subsidence, were developed in part later than, and in part perhaps concurrently with, these plutonic intrusions (Fig. 152D, 12). It is impossible in all instances to date the Mull vents, but the comparative lateness of some of them is clear from the fact that they break through the gabbros listed under *c*.

The volcanic pile must by now have reached a great height, but erosion has deprived us of any surface accumulation dating from this time.

(*e*) The great majority of the *early basic cone-sheets* are earlier than the gabbros of episode *c*, but a few cut the Ben Buie Gabbro. So far as is known, all that come in contact with the Corra-bheinn Gabbro are cut off by it (Fig. 152 D, 13 and 15).

The *Fourth Stage* was pre-eminently one of *deep-seated intrusion* All the rocks within the central subsidence-area were invaded by enormous ring-dykes (Fig. 152E, 16 and 17) made either of granophyre or quartz-gabbro magma. So numerous and powerful are these dykes that at the best only narrow "*screens*" of pre-existing rock have been spared between them. It must be remembered that it is these screens alone that provide us with the evidence from which the earlier history of the central caldera-region has to be deduced; hence some of the doubt as to the age relationships of certain of the ring-dykes to the agglomerates, and of the agglomerates to the pillow-lavas and to the early plutonic intrusions. That any consecutive history has been made out is still more amazing when one realizes that the ring-dykes and the adjacent screens have themselves been cut to pieces by hundreds of *late basic cone-sheets* (limits shown in a generalized way in Fig. 152E, LB). The period of intrusion of the latter was, however, a long one; and the phenomenon of a ring-dyke cutting some, and being cut by other cone-sheets is common. The late basic cone-sheets are centred on Loch Ba, as is shown on Plate II (C.2).

We do not know, for erosion has removed the evidence, whether any of the ring-dykes were feeders of vents that reached the surface; but it is more than probable that they were so, and that the volcano was still being added to at the surface both by agglomerates and by lava-flows, as suggested in Fig. 152E, 16.

The *Fifth Stage* saw the area of subsidence changed from the south-eastern (C.1) to the *north-western caldera*, centred on Loch Ba (C.2). This had already been marked out by explosive vents and by the intrusion of two large masses of augite-diorite (Plate II, 9 and 10) on either side of a N.W.-S.E. line through Loch

Ba. The different units of the C.2 area are grouped symmetrically about the same axis.

(*a*) The Glen Cannel *granophyre* (Plate II, 13) is a dome-shaped intrusion some 3½ miles long straddling the axial line. It appears to date from about the same time as the later members of the late basic cone-sheet suite.

(*b*) Large ring-dykes of *granophyre* cross the lower end of Loch Ba more or less at right angles, and have a symmetrical arrangement with reference both to the N.W. axis and to the point C.2 at the head of the Loch. They cut out many of the late basic cone-sheets, but are pierced by a few belated stragglers.

(*c*) The most remarkable feature, however, is the *Loch Ba ring-dyke of felsite* (Plate II, 14), already referred to (p. 362). Here the magma rose up along a roughly circular fault-line (Ring-fault) that defined the limits of the caldera, and solidified as a nearly vertical dyke which all but completes a circle round the area of subsidence. Associated with the ring-dyke are agglomerates, the distribution of which has suggested that the magma actually reached the surface through this ring-like orifice, and there formed a series of small vents comparable with the rim-volcanoes round the caldera of Askja (see p. 367).

The Loch Ba ring-dyke was the last effort of the volcano. After it, central activity ceased.

The Mull Swarm of North-Westerly Dykes.—The only intrusions later than the Loch Ba felsite are the last of the north-westerly dykes belonging to the *Mull Swarm of regional dykes* (Fig. 147 and p. 354), which had been intruded at intervals throughout the long history outlined above. The location of this swarm has suggested that Mull formed one of the magmatic centres from which the dykes drew their material. Their number is amazing. Only a small fraction have been traced inland, but along the 12½ miles of cliffs on the south-east coast, some 375 are exposed; and it is estimated that their combined breadths amount to about half a mile of rock. Some of the dykes reached the surface and developed small explosion-vents recalling the aligned craters or crater-row of Laki in Iceland (Fig. 8). Holmes regards the Tertiary dykes of the south of Scotland and north of England as part of the Mull Swarm.[1]

Devonian Cauldron Subsidences.

The conception of a central subsidence gave the key-note to the interpretation of the Mull volcano; but it had already in the first instance served to explain similar phenomena in connection with

[1] A. Holmes and H. F. Harwood, *Min. Mag.*, vol. xxii, 1929, p. 3.

the Old Red Sandstone volcanic centres of Glencoe and Ben Nevis in Lorne (Western Scotland).

The phenomena at Glencoe (Fig. 153) consist of a roughly oval area (nine miles long and five miles wide) of Lower Old Red Sandstone lavas with occasional agglomerates and sedimentary beds,

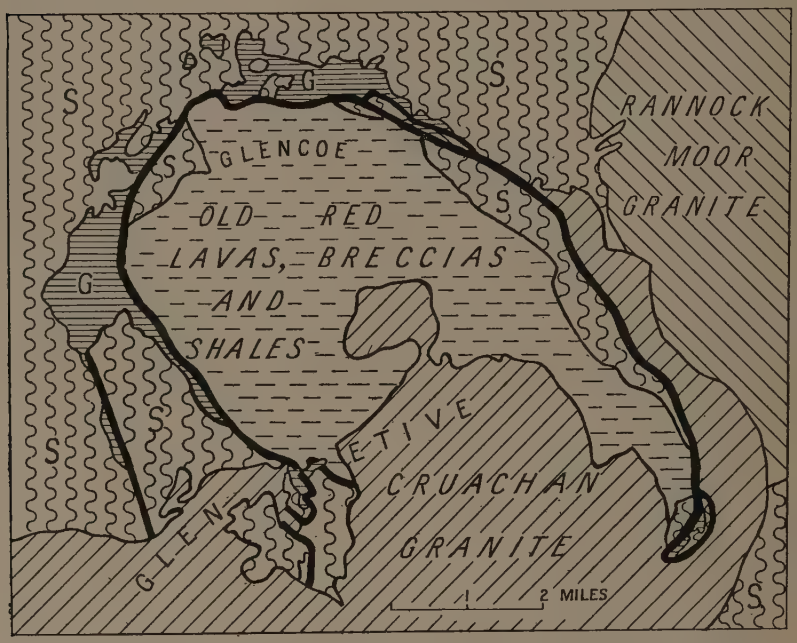


FIG. 153.—The Glencoe Cauldron-subsidence.

S, Highland Schists; thick lines, faults; G and close horizontal ruling, granite, etc., of the ring-dykes. Based on Clough, Maufe and Bailey.

resting on Dalradian schists, the whole elliptical block being surrounded by Highland schists and granite. The lavas have been let down by a ring-fracture which is expressed as a fault having an oval outcrop marked by a zone of intensely crushed breccia. Only for a short distance is the girdle of fault interrupted by an offshoot of the Cruachan granite (Fig. 153): elsewhere along the fault, ring-dykes (G) have been intruded. Clough, Maufe, and Bailey,[1] who investigated the region, came to the conclusion that we have in Glencoe a dissection of what they term a "cauldron-subsidence," the foundering, that is, of a more or less cylindrical column of the earth's crust into a potentially-liquid substratum. By its subsidence

[1] *Q.J.G.S.*, vol. lxv, 1909, pp. 611–76.

at Glencoe, the patch of lavas and underlying schists has escaped the erosion that has removed all traces of their continuations over the neighbouring district. These authors regard the phenomena observed as the underground expression of a surface arrangement similar to that found in the volcano Askja in Iceland. Askja consists of a huge caldera about 55 square km. in area, whose floor is some 1,300 feet below the surrounding basalt-plateau. Round the margin of the subsidence there is a series of *rim-volcanoes* that have poured lavas on to the caldera-floor. Spethman, who described Askja, considered that the crust as it sank had squeezed up the magma along the marginal fracture to feed the rim-volcanoes. The ring-dykes of Glencoe are thought by Clough, Maufe and Bailey to have been feeders of similar vents in Old Red Sandstone times, and the great patch of lavas to be a foundered portion of the ancient lava-plateau which by its subsidence had forced the magma upwards along the bounding ring-dykes.

The diagram (Fig. 154*a*) illustrates these authors' conceptions of a great mass of the crust dropping into a subterranean magma-chamber from which material is simultaneously displaced upwards. They extended the conception to the interpretation of the Cruachan Granite which cuts across the south side of the Glencoe lavas, and forms a great boss-shaped intrusion to the south-west. This they regard as the infilling of a subterranean cauldron caused by the foundering of a deep-lying block of the crust, as is diagrammatically represented on Fig. 154*b*. The foundered block must be thought of as breaking up and becoming dissolved in the underlying magma-zone.

Very similar phenomena characterize the granites of Ben Nevis.[1] Here there is a nearly circular and vertical-sided boss of older granite enclosing a similarly shaped, but smaller, newer, and inner granite which supports, as it were, a roughly circular block of lavas one and a half miles in diameter, that rest in their original position on schists. The lavas form the summit of the mountain. To quote Maufe: "The outer granite with its steep walls may be conceived as filling the void created by the gravitational sinking of a subterranean block into the underlying magma." Later, "the subsidence, now confined to the central area, again ensued, and was accompanied in complementary fashion by the uprise of the inner granite. But then an event occurred which, so far as we can tell, is peculiar to Ben Nevis. The roof of the subterranean cauldron gave way, and a block of schists, with its burden of lavas, subsided into the still liquid inner granite. . . . The sinking block in its descent must have dropped over 1,500 feet. We are thus led to the conclusion that the lavas

[1] H. B. Maufe, *Sum. Progress. Geol. Survey* for 1909, 1910, pp. 80–9.

of Ben Nevis, in spite of their great altitude, owe their preservation, like Glencoe, to subsidence."

It is extremely interesting to see foreshadowed in these ancient

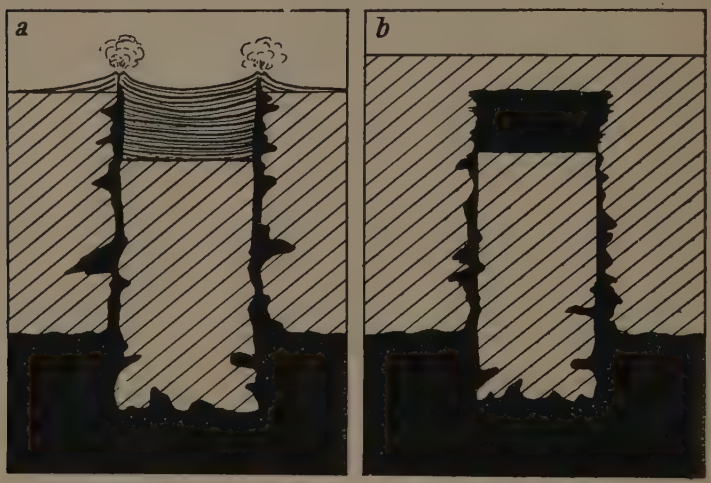


FIG. 154.—Diagrams of (*a*) subaerial and (*b*) subterranean cauldron-subsidences. After Clough, Maufe and Bailey.

but now deeply dissected plutonic phenomena, the same little-known type of igneous mechanism as characterized the Mull volcano of Tertiary age and Askja of Pleistocene or Recent date.[1]

[1] See note 2 on p. 350.

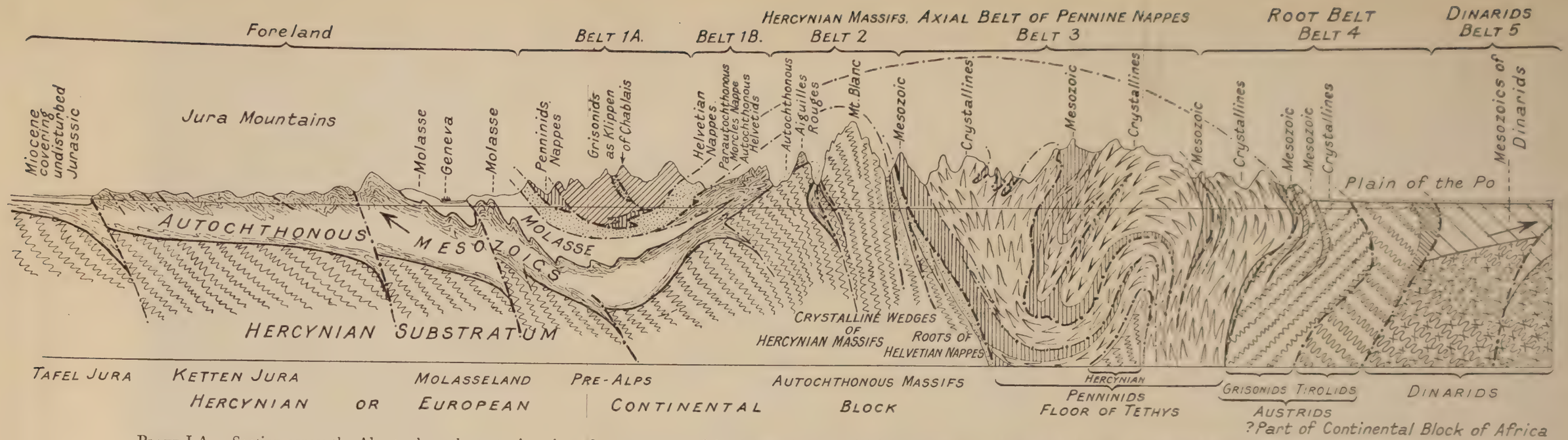


PLATE I.A.—Section across the Alps to show the tectonic units and arrangement of the nappes, based on Heim and Staub. Dots and dashes, thrusts and limits of the principal nappes.
Scale, horizontal, $\frac{1}{250000}$; vertical, $\frac{1}{83000}$.

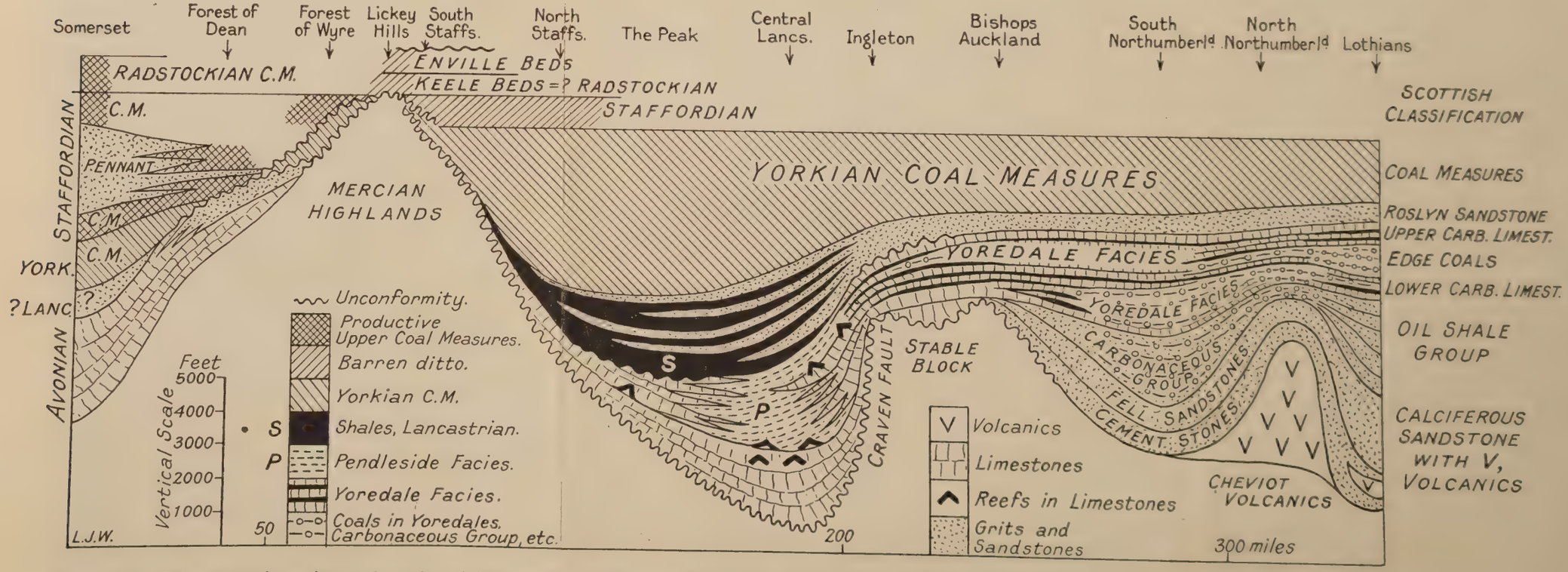


PLATE I.B.—Diagrammatic section to show the original variations in thickness and facies from south to north in the British Carboniferous along a line defined by the names at top. The variations in thickness correspond to variations in the amount of subsidence. The top of the Yorkian assumed horizontal to the north of the Lickeys.

PLATE II.—Map of the Tertiary volcano of Mull, based on the Geological Survey map, much simplified.

1, Derrynaculen Granophyre; 2, Glas Bheinn Granophyre; 3, Coire Mor Breccias (agglomerates); 4, Torness Felsite; 5, Corrabheinn Gabbro; 6, Ben Buie Gabbro; 7, Beinn Bheag Gabbro; 8, Beinn Mheadon Felsite; 9, Gaodhail Diorite; 10, Cruachan Diorite; 11, Loch Uisg Granophyre; 12, Loch Uisg Gabbro; 13, Glen Cannel Granophyre; 14, Loch Ba Felsite ring-dyke; 15, Sgurr Dearg Vents; C1, 1st Caldera, centred on Beinn Chaisgidle; C2, 2nd Caldera, centred on Loch Ba.

Close horizontal ruling—acid ring-dykes.
Close vertical ruling—basic ring-dykes.
Full black—felsites.
Stippled—Pre-Tertiary in anticlines.
White—Tertiary basalts.

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